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LASER SCANNER BEHAVIOUR AND ACCURACY

CYRAX^{TM} 2500 LASER SCANNER AND G.P.S. OPERATIONAL FLEXIBILITY: FROM DETAILED CLOSE RANGE SURVEYING, TO URBAN SCALE SURVEYING

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ABSTRACT:

The performance of the latest terrestrial laser scanners allows an expanded range of uses of these instruments. Even for laser scanners intended for architectural surveying, the maximum operational ranges reach, or in some cases exceed, 100-150 m. With such ranges, it is possible to utilize the instruments not only for measurements of single architectural elements but also for urban surveying of entire blocks or districts. This has raised the need to define a precise and reliable method to exploit the potential of these scanners.

In this paper, we report the preliminary results of a procedure designed to exploit both laser scanner technology and the Global Positioning System (GPS) for surveying on an urban scale. The GPS was used to determine the three-dimensional coordinates of the homologous points used to merge together the scans. Use of the GPS allowed us to record the scans even if they did not greatly overlap. Moreover, it was possible to conduct the surveying campaign with extreme elasticity; in fact, with the GPS, the scans are georeferenced automatically even if acquired at different times and the data can easily be used for cartographic or cadastral purposes.

1. INTRODUCTION

In previous studies (Balzani et al. 2001; 2002), we demonstrated the potential applications of laser scanner methods in architectural surveying. The instrument used was the Cyrax™ 2400 manufactured by CYRA Technologies. Regarding the problem of recording multiple scans, we studied the applicability and quality of automatic procedures of recognition of the flat reflecting targets suggested by the manufacturer. The results can be summarized as:

- automatic recognition of the flat reflecting targets was performed with good precision and repeatability when the distance from the object was no greater than 50 m and the inclination with respect to the plane of the target was between a frontal scan and a 45° angle;
- for scans at distances over 50 m and inclinations greater than 45°, it was not possible to rely on automatic target recognition. However, it was possible to perform manual recognition of the target centre, with more than satisfactory results;
- even at large distances, measurement and restitution of the object's natural shapes were carried out with excellent precision.

On the basis of the results of these tests, we decided to conduct new experiments to evaluate the potential of the laser scanner at its maximum range in order to survey large parts of a territory in the least possible time. In addition to surveying speed, one of the problems that must be resolved in an urban application is the need to record a large number of scans without a progressive decrease in precision (effect of error propagation). After some initial tests using a spherical target, we decided to use the GPS to determine the three-dimensional coordinates of a sufficient number of targets for use in the merging of the various scans. The GPS presents numerous advantages: it allows one to quickly obtain the three-dimensional coordinates of points (in the WGS84 geocentric reference system) with centimetric precision; the times of GPS surveying (performed as described later) are comparable to those of the laser scanner and, with suitable "target/GPS" adapters, it can be performed contemporaneously; surveying of a territory (even a very large one) can be carried out in different sessions, spaced in time, all without the need to create and measure a reference network; using a master GPS station of known coordinates, the survey is framed within the WGS84 system and thus, after the appropriate coordinate transformations, can easily be used for cartographic and cadastral purposes.

In the following sections, we describe the proposed methodology and report the results of our preliminary tests.

2. INSTRUMENTATION

The scanner is composed of an impulse EDM and various optical-mechanical apparatuses (rotating mirrors, servomechanisms, etc.). The EDM measures the time each laser impulse takes to go from the source to the measured object and then return to the point of emission. This technology, based on the "flight time" (or LIDAR), can be used with any refracting surface. The laser impulse is guided by small rotating mirrors regulated by servomotors: in this way, a "laser paint" is activated which moves over the object to be measured. The scan appears as a consecutive series of columns of sequential points that quickly form a three-dimensional image. The accuracy of positioning of single points in space depends on the accuracies of the distance measurements and the angular measurements of the small rotating mirrors. The polar coordinate can be easily transformed in 3D Cartesian coordinate in a local frame

For a detailed description of the instrumentation, see the bibliographical references.

In the time between our previous studies and the present one, the Cyrax™ 2400 laser scanner was replaced by the Cyrax™ 2500 model, available in Europe in early 2002. The instrument's software and preliminary data analysis also changed; the new software is called Cyclone 3.2 and replaces the previous C.G.P. 2.1.

The study is obviously strongly influenced by the characteristics of the instrumentation used: even small operational differences can render the surveying procedures very different.

The main differences between the 2500 model and the previous one are:

- the maximum usable range increases to 230-250 m;

- the automatic procedures of flat target recognition can be used at distances greater than 50 m (up to 75-80 m);
- the possibility to perform automatic recognition of 6" dedicated spherical targets;
- the possibility to perform a manual search on the point cloud of the desired area (e.g. relative to the position of a flat or spherical target or of any natural point) and to launch a more detailed survey on it (the dimensions of the area and the points density is set by the operator); this possibility was greatly exploited in the present study because it allowed us to position the target/GPS system at distances greater than 75-80 m (even up to 150-200 m).

We now describe the main characteristics of the instrumentation:

LASER SCANNER CYRAX 2500™			
Company	**Country**	**principle**	**eye safety class**
CYRA technology	U.S.A.	t.o.f	Class 2
PERFORMANCES			
max. range on natural targets	**horizontal scan range**	**vertical scan range**	**scan mechanism**
250 m	44 gon	44 gon	rotating mirror
horizontal angle readout accuracy	**vertical angle readout accuracy**	**range accuracy**	**point accuracy @ 50m**
±3.8mgon	±3.8mgon	±4mm	±6mm
OTHER FEATURES			
beam divergence	**scan rate**	**dimensions**	**weight**
≤6mm @50m 7,6mgon	1 column/sec @1000 pts/column	400 x 330 x 430mm d x w x h	20.5kg

Table 1. CYRA specifications about Cyrax 2500™

Figure 1. Laser scanner Cyrax 2500™

Figure 2. Cyclone 3.2

As is known, the GPS is a positioning system based on reception of radio signals emitted by a constellation of artificial satellites in orbit around Earth. For precise positioning, the GPS is used in relative mode, with at least one pair of receivers: a master receiver placed on a vertex of known coordinates in the WGS84 geocentric system and other rover receivers on the points to be measured (Hoffmann – Wellenhof ;1997).

In the present study, we used four Ashtech ZXII double-frequency geodetic receivers in rapid-static mode, with the session duration and sample rate set to allow a centimetric precision of single baselines in normal situations. The baselines were analysed with GeoGenius™ 2000 commercial software.

Figure 3. G.P.S. Antenna and receiver

3. AIM OF THE EXPERIMENTS

As mentioned in the introduction, one of the aims of the experiments was to determine, with the GPS, the coordinates of a sufficient number of points to use for the merging of scans performed with the laser scanner.

Merging of the various point clouds is based on a rototranslation in space. This transforms the coordinates of all the points of the cloud (each scan is referred to a "local" frame centred on the laser scanner) into a unique or "global" frame defined by the user, which can coincide with the local frame of a predefined scan.

Therefore, for each scan, six parameters of the transformation must be calculated (the three rotations of the axes and the components of the vector of translation of the origin of the local frame); using three homologous points and a least squares procedure, it is possible to calculate the parameters of the rototranslation with a degree of superabundance of three; thus it is possible to apply the transformation to the entire point cloud.

Normally the homologous points allowing an accurate recording between two or more scans are constituted by flat reflecting targets positioned on the object to be measured; the scans to be joined must have a large area of overlap and the position of the target must be analysed from time to time, making the surveying of large territories very difficult (hereafter we use the term territorial scale surveying).

The idea used in these experiments was to successively perform all the scans necessary to cover the survey area and, for each of them, to position at least three GPS antennas able to furnish the coordinates of three homologous points (between the GPS and laser scanner system) to be used to calculate the parameters of the transformation. In this way, the WGS84 geocentric system was used directly as a "global frame" for all the scans. Naturally, the GPS antenna, more precisely its phase centre, could not be used directly as a homologous point (measured by both the GPS and laser scanner); it was necessary to make a suitable device to allow the simultaneous positioning of the GPS antenna and a classical flat reflecting target. In this way, the GPS measurement furnishes the WGS84 coordinates of the antenna's phase centre, while the laser scanner provides the coordinates of the centre of the reflecting target in the local frame of the scan. At this point, the WGS84 coordinates of the antenna's phase centre must be transferred to the target centre, an operation requiring an initial control and calibration of the adapter devices (described later).

The advantages of this solution are obvious:

- *contemporaneous measurements*; the time component is an important factor in territorial scale surveying;
- *flexibility of use of the instrumentation:* the proposed method satisfies the requirements of the single instruments without creating annoying overlaps of one on the other;
- *areas of overlap reduced to a minimum*; with the proposed method, no overlap between the different scans is required for the recording;
- *planning of the surveying directly in the field*; exploiting the operational elasticity of the GPS antennas, it is possible to decide on the spot which portion of the territory is to be scanned and where to position the reference antennas, without having to plan the session in the laboratory.

3.1 Planning and calibration of the adapter devices

To achieve the described aims, we designed and built a suitable adapter equipped with a Wild fillet that allowed us to contemporaneously position both the flat reflecting target and the GPS antenna on a topographical tripod and a sideboard equipped with a spherical level.

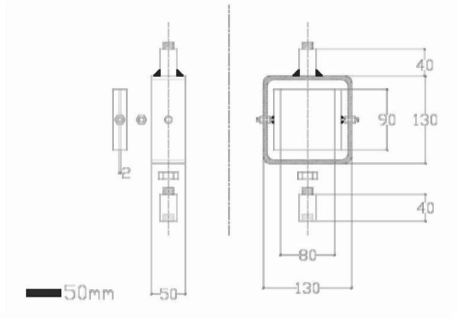

Figure 4. Design of the adapter

To contemporaneously perform the GPS and laser scanner measurements, we equipped the plane holding the reflecting target with two orthogonal axes of rotation that allowed us to maintain it in a frontal position with respect to the scanner; in this way, automatic target recognition was possible in the scanning phase and manual recognition was facilitated at great distances.

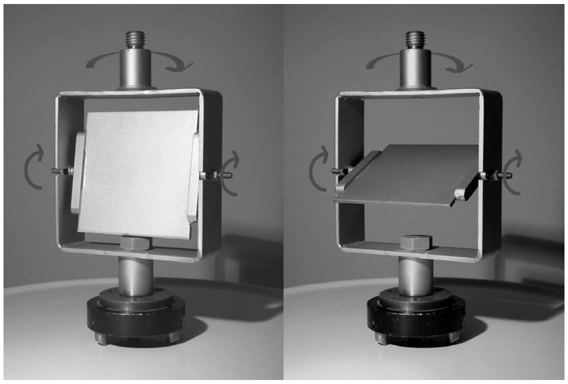

Figure 5. The adapter we built

For each adapter, we first performed a control procedure to verify the correctness of its construction. In particular, we measured the planimetric difference in the position of the target centre with respect to the vertical for the station point and the change in position of this centre when the adapter was rotated around the vertical.

In addition, we performed a careful calibration that allowed us to assess the vertical offset between the coordinates of the phase centre of the GPS antenna and the coordinates of the centre of the flat reflecting target positioned on the adapter.

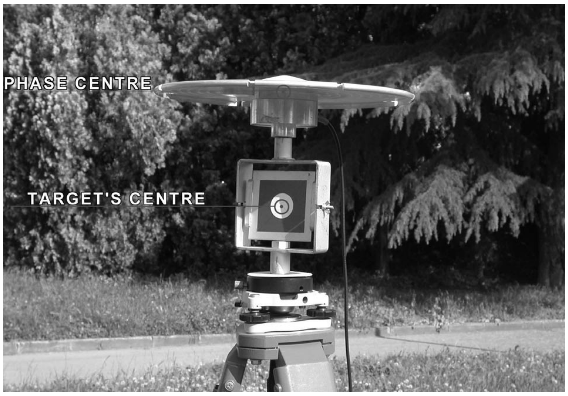

Figure 6. The vertical offset between the phase centre and the target's one

4 EXPERIMENTS

We now describe the organization of the survey and the data collected.

4.1 Organization of the survey

The first part of the survey lasted for 2 days, for a total of about 16 hours of work. We chose to take the scans in a real situation of territorial scale surveying. Thus, we conducted the experiments in an urban area, dealing with problems like traffic, poor visibility of the GPS satellites and the planning of numerous surveying stations.

In accordance with the above-mentioned premises, the surveying session was organized as follows:

- identification of an appropriate station point for the master GPS antenna. The characteristics of this point must ensure a good distance from obstacles, like buildings and vegetation, and from reflecting surfaces (which could produce multipath errors); moreover, it should be in the centre of the area to be surveyed so as to have short baselines and, if one wishes to use the survey for cartographic and cadastral purposes, it should be a vertex of known WGS84 coordinates (if a vertex of known coordinates is not available, one can always carry out a subsequent survey to frame the master station in a pre-existing network or one can use the international IGS network of permanent GPS stations).
- positioning of the laser scanner station on the preset point;
- analysis of the scanner's field of view and decision about the points on which to position the three adapters with the rover GPS antennas. The laser scanner is equipped with a digital camera that acquires the image of the area to be surveyed; with this image, it is possible to decide on the areas in which to position the adapters;
- positioning of the adapters and acquisition of the GPS data.

For each antenna, we set a sample rate of 3 seconds; with a session duration of at least 15 minutes, this provides a sufficient number of epochs for determination (with centimetric precision) of the GPS point in rapid-static mode. To exploit the potential range of the instrument (up to 250 m), we tried to choose station points of the rover GPS antennas that were well distributed (also in depth) within the field of view of the single scan; in this way, we could reduce the hinge effects that can result if they are too close together (even a slight rotation of the model in the junction zone generates a high linear error if multiplied by an arm of 250 m).

Figure 7. The three antennas in the scanner's field of view

- after the adapters were positioned and their effective presence in the scanner's field of view was checked (e.g. with a rapid wide-grid scan), we began the actual scanning. Assuming that the aim of territorial scale surveying is large-scale reproduction (1:500; 1:1000), it is necessary to have a precision of the measured detail points of 10 cm.

As a first approximation, the precision of surveying performed with the laser scanner can be estimated as the combination of the intrinsic precision of restitution of the single collimated point (≅ ±6 mm) and the spacing of the projective grid. In fact, due to the nature of the laser scan, the object is defined by a huge mass of indiscriminate points; recognition of the characteristics of the object (e.g. restitution of the edges of a building) is performed by interpreting the point cloud and exploiting the level of detail acquired. We chose to survey all the buildings in the field of view with a grid of at least 5 cm. This was achieved by setting the projective grid spacing at 5 cm at the distance of the farthest building;

- execution of automatic recognition of the targets when possible; in fact, for distances less than 80 m, the Cyrax™ 2500 laser scanner can recognize the shape and reflectance of the dedicated flat targets and carry out fine recognition with a millimetric point density;
- manual recognition of the most distant targets; this important innovation of the scanning procedures of the 2500 model (with respect to the previous model) was fundamental for our experiments. In fact, it was possible to manually collimate the target on the point cloud (or the zone in which it was situated) and then perform a fine scan of it with millimetric point density, thus measuring the same level of detail as with the automatic procedure. The same procedure would have been very difficult with the previous instrumentation because collimation of the scanning zone was based only on the low-resolution digital image acquired by the scanner and recognition of a small object (like the target) at great distances was practically impossible.

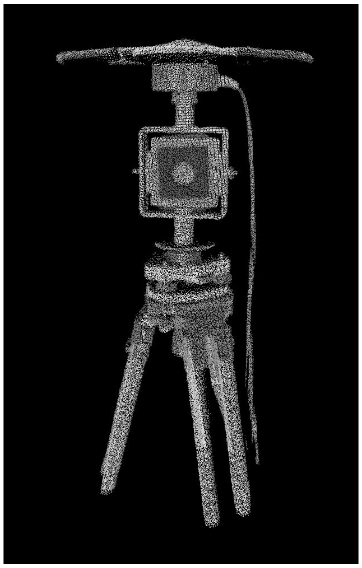

Figure 8. Fine scan on the adapter and the antenna

4.2 Surveyed data

We set up 12 scanning stations, for a total of about 12.458.302 measured points. The following table describes the scans.

scan	number of surveyed points	max distance on natural point	distance between scan and GPS 1	distance between scan and GPS 2	distance between scan and GPS 3
1	2.078.835	258,61m	26,09m	56,47m	29,52m
2	1.274.512	128,51m	29,49m	36,63m	56,43m
3	625.892	260,06m	36,61m	45,44m	75,31m
4	1.106.637	455,69m	48,80m	63,90m	73,28m
5	1.332.457	204,65m	33,31m	155,91m	13,73m
6	425.173	149,47m	155,91m	-	-
7	447.037	118,06m	-	-	-
8	973.540	331,38m	106,36m	29,58m	35,67m
9	648.613	132,37m	26,59m	22,66m	39,79m
10	1.508.824	235,39m	72,84m	47,32m	28,70m
11	1.061.557	162,99m	44,85m	89,50m	46,78m
12	975.225	214,27m	28,55m	47,22m	127,47m

Table 2. Information about the clouds surveyed

Stations 6 and 7 refer to measurements of a terrestrial surface with low satellite visibility. In fact, it consists of a narrow road bordered by tall buildings. In this case, as in similar ones, we decided to use the maximum number of positionable antennas (e.g. only one antenna was positioned at station 6) and the classical recording method (i.e. application of flat targets in a zone of overlap between two scans).

5. RESULTS

5.1 Recording of the scans

All the scans were analysed on the basis of our experience in the previous studies; in particular, before starting to record, it is fundamental to perform a control and possibly a manual adjustment of the recognition of the target centres proposed by the scanner.

It is also appropriate to cancel all the erroneously acquired information due to disturbances (e.g. pedestrians and moving vehicles), so as to make the model as legible and interpretable as possible.

We then used the recording procedures included in the dedicated software and we evaluated the resulting three-dimensional residuals by subsequent application of the calculated transformation.

The coordinates of the phase centres of the GPS antennas were transformed into local topocentric coordinates centred on the master; in this way, we could directly apply the offsets between the target and phase centre of the antenna.

We now report the results in a frequency histogram with 1 mm classes:

As can be seen from the histogram, 67% of the residuals are smaller than 6 mm, which is the manufacturer's stated precision of the laser scanner for acquisition of a single point.

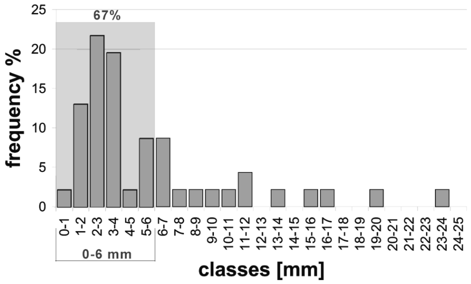

Figure 9. Histogram presenting 3D residuals' module

5.2 Data analysis

We now report some visualizations of the point clouds.

Visualization in raster format prevents the recognition of much information which instead is perfectly interpretable by direct analysis of the three-dimensional data.

In figure 10 and 11 we show two single scans; the arrows point out the position of G.P.S. antennas and adapter. In figure 12 we show the model after the merging of the two scans. By using this procedure many times we obtained the entire model.

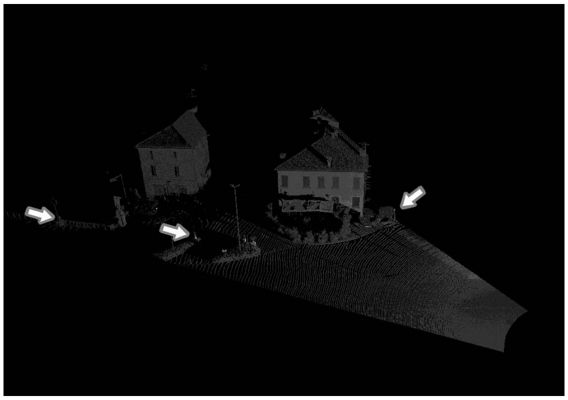

Figure 10. A single scan. The arrows point out the position of the G.P.S. antennas

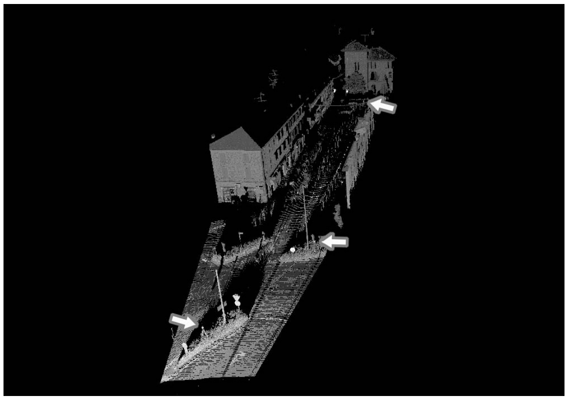

Figure 11. A single scan. The arrows point out the position of the G.P.S. antennas

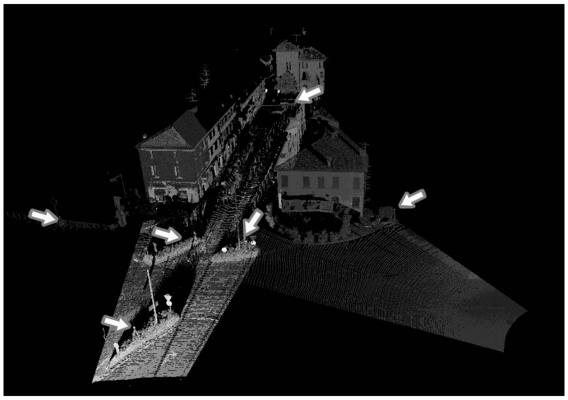

Figure 12. The two scans merged together

6. CONCLUSIONS

Preliminary tests of the potential advantages of combining laser scanner and GPS surveying fully justify the use of this method. The precision obtained in the recording procedures and the direct analysis of the complete model have demonstrated its good reliability.

At the moment, we are conducting a study to evaluate the precision of the model and to assess the applicability of the method to larger portions of a territory.

Use of the survey for cartographic or cadastral purposes can be hypothesized on the basis of the results of the restitution tests.

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EXPLORATIONS INTO THE BEHAVIOUR OF THREE DIFFERENT HIGH-RESOLUTION GROUND-BASED LASER SCANNERS IN THE BUILT ENVIRONMENT

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KEY WORDS: Laser scanning, Close Range, Terrestrial, Accuracy, Performance

ABSTRACT:

Today, high-resolution ground-based laser scanning has entered the field of distance measurements for documentation of objects. However, the documentation of high-resolution ground-based laser scanning with respect to its specific characteristics and behaviour is still in its early stages. The aim of present work was to contribute to the evaluation and documentation of such systems. Three systems was included, the Cyrax 2500, Optech ILRIS-3D and the Riegl LMS-Z210, all based on the pulsed time of flight (TOF) laser ranging technique. The systems distance measurement accuracy was investigated, the systems possibilities to resolve test objects representing the built environment was briefly evaluated and different materials influence on the results was looked into. Modelled surface precision was found close to vendor specifications; still some points deviated relatively far from modelled surfaces. For Cyrax with a modelled precision of 2 to 4 mm maximum errors of 9 to 20 mm was found. ILRIS-3D with a modelled precision of 8 to 12 mm showed maximum errors from 35 to 65 mm. Due to system limitations a coarser scanning resolution was set for the LMS-Z210. A modelled precision of 20 mm and maximum errors of 52 to 75 mm was found for the LMS-Z210. When comparing distances measured with the systems to "true distances", Cyrax was found to be within 2 mm of the true values over a range of 85 meter. ILRIS-3D deviated 2 to 22 mm from the "true distances" and the LMS-Z210 deviated 7 to 24 mm from "true distances". For all three systems strange effects along edges of objects was found. For the ILRIS-3D the edge effects was relatively large compared to the other systems. The edge effect was also found to limit the possibility to resolve small objects and objects close to each other. Cyrax was found to resolve details best. The Cyrax system showed problems in measuring of objects with low reflectivity. However, major dropout of points only occurred beyond the recommenced maximum range of 50 meter.

1. BACKGROUND AND THEORY

1.1 Background

This work is a first contribution from the Gävle GIS Institute in its exploration into the behaviour of high-resolution ground-based laser scanners and its use in the built environment.

Three different laser scanners are included in the tests: One Cyrax 2500 from Leica Geosystems, recently acquired by the University of Gävle, one Ilris-3D from Optech and one LMS-Z210 from Riegl. The Swedish Defence Research Agency and its Laser Systems department in Linköping provide the systems from Optech and Riegl. All three systems measure distances with help of the time-of-flight distance measurement technique. As a reference, one very accurate reflectorless measuring geodetic surveying instrument, a Trimble 5600 DR200+ total station, will be used.

The tests focus on the scanner's behaviour in different important situations for documenting the built environment. The focus is not on a direct comparison of the scanners. Instead, the focus is in trying to find the unique characteristics for each scanner, and, although the scanners have different specifications, finding possible similarities and differences between the different scanner behaviours in problematic situations.
In general, the tests can be divided into three parts. The first part covers the systems distance measuring accuracy; the second part tests how well the point clouds actually represents reality; and the third part consists of tests on how different objects reflectivity influence the performance of laser scanners. Activities such as detecting edges, scanning through small openings, recording from extreme angles of incidence and measurements on materials with different reflectivity will be examined.. For all these situations or, combination of situations, it is important to understand where possible erroneous points can be found to be able to evaluate and make use of the resulting point-clouds in a comfortable way.
Two test objects have been specially designed and built for evaluating laser-scanning results for problematic areas in the built environment. One of the test objects consists of parallel mounted plates, approximately 60 by 40 centimetres in size, with fixed distances between, and with cut-outs of known geometrical figures in the front plate. The plates are made of a high reflective material and all measures, including size of cut-outs, are within sub-millimetre accuracy. This object is specifically designed to give answers to the behaviour of the different scanner results from detecting edges and scanning through small openings. To be able to evaluate different angle of incidences and surface structures a one cubic meter box has been built. Pasted on the sides are different surface materials and the box is mounted on a centre axis to allow the possibility to rotate it. In addition, the top of the box is equipped with points of attachment for specific registration spheres, and for targets of different sizes for tests of distance measurement accuracy. A target of materials with different reflectivity will also be used in the tests.
Besides information about how the different tests were realised, and the results from the tests obtained, the goal is to present possible methods to avoid "unwanted" data, or identifying were "unwanted" points can be found in the point-clouds.

Though the systems before the tests took place had been used in research and for educational purposes as well as in real world "production" projects, there were some doubts about their status. The Cyrax had shown strange effects during outdoors night-time scans in complete darkness, and surprisingly loosing points on some materials. The answer to this was not given before the tests took place. The ILRIS-3D had been delivered to the Swedish Defence Research Agency in a rush and had not been perfectly calibrated by Optech before delivery.

1.2 Pulsed time of flight laser ranging

All three systems included in the test make use of pulsed time of flight (TOF) laser ranging, probably the most obvious method of operating a laser ranging system because the actual time of flight is measured directly. Time measurement is performed by accurately measuring the time of flight of the laser pulse from exiting the laser, reflect off the object, returning to the laser, detected by the system and stopping the time of measurements. Knowing the speed of light and multiplying with half the travel time gives the actual distance to the object. One advantage of using pulsed light is the possibility of transmitting a high amount of energy in a very short time, which limits the influence of background noise. However, very accurate systems require short pulses and going to short pulses limits the possible amount of energy in the pulse. The basic problem of a TOF laser ranging system is to detect exactly the arrival time of the reflected light pulse. A fast time measuring device and good signal processing increases distance measurement accuracy. Looking at some specific continuos wave laser ranging systems the pulsed systems is comparably slow due to the relatively low repetition rates for the pulses.

2. TESTING THE SYSTEMS

2.1 Testing facilities

The tests were realised at the Swedish Defence Research Agency in Linköping, indoors in a room suitable for testing measurements over relatively long distances. Lightning condition was uniform for the whole test range, and with the light from fluorescent (strip) lighting switch on. The temperature and humidity in the room was normal and well within the specified limits for the systems used in the tests. The air was normal and free from possible dust interfering with the measurements.

2.2 System specification

Three different high-resolution ground based laser-scanning systems were included in the tests: One Cyrax 2500, recently acquired by the University of Gävle, one Optech Ilris 3-D and one Riegl LMS-Z210. The systems from Optech and Riegl were placed at the test disposal by the Laser Systems department at the Swedish Defence Research Agency in Linköping.

As a reference, one reflectorless measuring Trimble 5600 Total Station, owned by the University of Gävle, was used.

2.2.1 Cyrax 2500

The University of Gävle, Sweden, owns the Cyrax 2500 used in the tests. The scanner was purchased late 2001 for use in research, especially in the built environment, and in special education programmes.

The basic components of the Cyrax system are the scan head, a specially design tripod, a power box, the laptop computer and specially design targets. The scan head consist of the actual laser scanner and a CCD camera and is connect as a unit to the specially design fork mount. The fork mount gives the possibilities to easily pan and tilt the scan head in a proper position to the targeted area. The Cyrax system is powered by a specially designed power box and can either operate from AC line power connected to the box our from up to two batteries installed in the box. Fully charged two batteries are expected to power the system for up to 8 hours.

The Cyrax uses a pulsing, passively Q-switched green laser that scan the object as a cloud of point. This point cloud is a representation of actual object's surface in three dimensions. High-speed motorised mirrors deflect the laser pulse as it exits the system and sweeps the laser over the object. The Cyrax is capable of scanning up 1000 points per second and with a single-point position accuracy of ±6 mm.

With help of a laptop computer connected to the system and the Cyrax Cyclone software, the scanner functionality is controlled. Furthermore, the Cyclone software provides powerful tools for e.g. modelling, meshing and measuring of distances within the point cloud. The Cyclone software also includes tools for importing of other scanner systems data as well as tools for exporting of data. It is also possible to export modelled objects to common CAD software, e.g. to AutoCad and Microstation.

The Cyrax 2500 is the latest version of high-resolution ground based laser-scanning systems from Cyra Technologies. Development of the Cyrax system was a joint project between Cyra Technologies, Los Alamos National Laboratory and Massachusetts Institute of Technology (MIT) Lincoln Laboratory. The Los Alamos Physics Division developed the precise time measuring circuit, Cyra Technologies was responsible for developing the software for the system, today the software package Cyclone, and MIT Lincoln Laboratory developed the laser for the system. Since February 2001 Cyra Technologies Inc. is a wholly owned subsidiary of Leica Geosystems AG.

2.2.2 Optech ILRIS-3D

Swedish Defence Research Agency and its Laser Systems department became an owner of one Optech ILRIS-3D system in middle of year 2001. The Laser Systems department was one of the first buyers of ILRIS-3D system.

The ILRIS-3D has a distance measuring accuracy close to what can be achieved with the Cyrax system. It is twice as fast as the Cyrax both much slower than the Riegl system. The system is controlled with help of a hand held PDA and measured data are stored on ATA flash cards. This eliminates the need for a laptop computer during field operation. However, back in the office data needs to be downloaded from flash cards to a computer for further processing. The system also includes tools for exporting of data.

2.2.3 Riegl LMS-Z210

Swedish Defence Research Agency and its Laser Systems department has been an owner of the LMS-Z210 system for some years. The system is a rugged and fully portable sensor especially designed for the rapid acquisition of high-quality distance measurements under high demanding environmental conditions. The LMS-Z210 records not only position and intensity values but also a RGB value for each measured point. The speed of the system is considerably faster than both the ILRIS-3D and the Cyrax, but the distance measuring accuracy is relatively low. The beam diameter or spot size is also considerably large then for the two other systems included in the tests. However, the LMS-Z210 has a much larger field of view than the ILRIS-3D and the Cyrax.

With help of a laptop computer connected to the system and the Riegls 3D-RiScan software, the scanner functionality is controlled and measurements from the scans are processed and visualised. The 3D-RiScan software also includes tools for exporting of data. The colour information (RGB-value) in each registered point gives possibilities to direct colour textured 3D-model generation, e.g. into VRML models.

	Cyrax 2500	**ILRIS-3D**	**LMS-Z210**
Wavelength	532 nm	1540 nm*	905 nm*
Min. range	1.5 m	-	2 m
Max. range	100 m 50 m recommended to objects with 5%-100% reflectivity.	To objects with 4% reflectivity up to 350 m. To objects with 20% reflectivity up to 800 m.	To objects with 10% reflectivity up to 150 m. To objects with 80% reflectivity up to 450 m.
Beam diameter	≤6 mm from 0 to 50 meter.	15mm@50 meter. 20mm@100 meter.	40mm@short distances. 300mm@100 meter.
Single point distance accuracy	±4 mm.	±10 mm.	25mm@25 mm resolution + distance depending error ≤±20ppm.
Single point position accuracy	±6mm@1.5-50m range.	±7mm@50m ±10mm@100m	-
Minimum (horizontal/ vertical scan increment)	0.005 mrad 0.25 mm point-to-point spacing @50m.	0.17 mrad 8.5 mm point-to-point spacing @50m.	1.256 mrad 62.8 mm point-to-point spacing @50m.
Field of view (horizontal/ vertical angle)	40°/40°	40°/40°	333°/80°
Max. data acquisition rate	1000 points per second.	2000 points per second.	28000 points per second. Mean 9330 pps.

*The wavelengths of Optech and Riegl are not confirmed.

Table 1. System specifications.

2.2.4 Trimble 5600 DR200+

The measurement technique used in DR200+ is based on the pulsed TOF distance measuring. To reduce the influence of background noise a unique method of taking the average of many pulses, and determining the shape of the pulse before the transit time of flight is calculated, increases the accuracy of the system. The distance measuring accuracy of the system is ± 3 mm + 3 ppm from 5 to 200 meter.

2.3 Systems range precision and accuracy

To determine the distance measuring accuracy, distances measured with each of the scanner systems were compared to distances measured with a total station. Five test targets were placed in the area to be scanned as in figure 1.

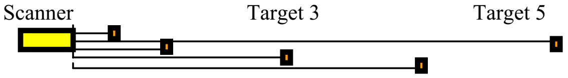

Figure 1. Distribution of test targets

The distance from the scanner to the first test target was approximately 5 meter.

From target 1 to target 2:	5 m
From target 1 to target 3:	25 m
From target 1 to target 4:	50 m
From target 1 to target 5:	80 m

Table 2. Approximate distances between test targets.

The length of the test room limited the range for which the systems distance measuring accuracy could be tested.

At first, one system was placed in position and the area to be scanned, including the five test-targets, was scanned 10 times. Thereafter the second system was approximately placed in the same position and a 10 times scan of the same area was carried out. Finally, the third system went through the same process. All the scans were made within the same day.

The test targets were all placed at the same height above the floor and the systems approximate origin were placed at the same height as the centre of the targets. The test targets were levelled and placed as close as possible to be parallel to the position for the systems. After the test-targets had been placed in position, they were left in the same position throughout the whole test. Before scanning, when placed in the actual scanning position, the system as well was levelled. The levelling was done with help of water level equipment since the tested systems was not equipped with any built-in levelling possibilities.

Levelling and positioning was done to make sure that the systems measurements were all carried out under almost similar conditions.

The test targets are all made of plain wood and considered common material for built environments. Being made by our own the test targets did not favour any of the systems. To be able to identify specific positions on the targets the centre of the target, and a square round the centre, was marked with a thin layer of red aerosol spray-paint (see figure 2). Five specific positions were later used to measure distances between when comparing the scanner system distances with distances measured with the total station.

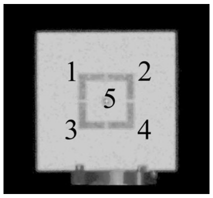

Figure 2. Test target showing the 5 specific positions

With help of the Trimble total station, capable of measuring reflectorless, all five positions on all test targets were determined. The positions were over-determined, and from all the measurements, an averaged value was given to each position.

Cyclone was later used to evaluate the scanner data from all the systems. Data from the Optech system was converted in to an ASCII text-file exchange format, the .ptx file format, and thereafter imported to Cyclone. The .ptx file format includes the X, Y, Z and intensity value for measured points. For the Riegl system, the data was imported by using the Riegl .3dd file format.

In the Cyclone software, each test target was modelled into a plane. A best fitting algorithm for a plane, available in Cyclone, was used. For the best fitting of a plane to each target, measured points on the test targets, from all ten measurements, were used.

From the planes, at the five specific position spots that had been measured with the Trimble, point-to-point distances between the different planes, for each system, were measured.

By fitting a plane to the test target the precision for each system in measuring towards the test targets was given. Furthermore, using the measurements from the Trimble as true values the accuracy for each system was tested.

2.4 Representation of reality – scanning of purposely built test objects.

Two test objects have been specially designed and built for evaluating laser-scanning results for problematic areas in the built environment. One of the test objects consists of parallel mounted plates, approximately 60 by 40 centimetres in size, with fixed distances between, and with cut-outs of known geometrical figures in the front plate. The plates are made of a high reflective material and all measures, including the cut-outs, are within sub-millimetre accuracy. To be able to evaluate different angle of incidences and surface structures a one cubic meter box has been built. Painted on the sides are different surface materials and the box is mounted on a centre axis to allow the possibility to rotate it. In addition, the top of the box is equipped with points of attachment for specific registration spheres. A third object was constructed out of two thin metallic plates and used for testing the problem of measuring and modelling small opening angles between surfaces. The plates were position either with the plate angle opened (>) towards the scanner or closed (<) towards the scanner. All this special objects were placed together so they could be measured all at the same time. The measurements of the objects were done with all three scanners more or less at the same time. The scanners were placed with a very small offset to each other, having all scanner heads within a box of approximately 3.0x0.5x0.5m size. Scans were made with different resolutions, at different ranges, and with different positioning of the objects between each scans. The box was rotated around the central axis into eight different positions turning it round a full circle. When positioning the box the 60 by 40 cm plate was also positioned into its different angle of incidences before each scan. The thin metal plates were also placed in position and the opening angle was measured before each scan.

These objects were used when evaluating the behaviour of the different scanner results in detecting edges, scanning into small openings and resolve small objects. The influence from the different materials on the box was also to be evaluated.

2.5 Measurements on targets with known reflectivity

A target with four areas with different reflectivity was used provided by the Laser Systems department. The reflectivity ranged from 20% black to 90% white and included two grey-levelled areas on the target with know reflectivity.

The measurements of the objects were done with all three scanners more or less at the same time. The scanners were placed with a very small offset to each other, having all scanner heads within a box of approximately 3.0x0.5x0.5m size.

The test target was scan with a point-to-point spacing to give to give acceptable amount of points on the target.

The target was placed in eight different positions, and in all positions being almost perpendicular to the systems scanning direction. The positions went from 10 to 80 meters with 10-meter increment and with the meter range being scanned twice, as the first and the last scan.

Possible linearity in recording reflectivity, possible drift over time and possible problems in register intensities on same reflectivity material will be evaluated.

3. RESULTS

3.1 Systems range precision and accuracy

For all the systems, a specific point-to-point spacing at a certain distance was set. See following tables. Ten repetitive scans of the object area was done for all the systems. For each system, including the points from all ten scans, all points for each target were modelled into a plane. Only points well inside the targets were included in the modelling. Number of points gives a figure of how many points that were included in modelling each test target plane.

	Cyrax 30 mm point-to-point spacing@60m		
	Standard dev.	Max error	Number of points
Target 1	3	15	59459
Target 2	3	11	14664
Target 3	2	9	1690
Target 4	3	14	632
Target 5	4	17	250

Table 3. Modelled precision for Cyrax 2500.

	Cyrax. 10 mm point-to-point spacing@60m		
	Standard dev.	Max error	Number of points
Target 1	3	16	481687
Target 2	3	12	135449
Target 3	2	16	15944
Target 4	3	17	4221
Target 5	4	20	1954

Table 4. Modelled precision for Cyrax 2500.

The Cyrax show figures close to what can be found in the specification for the system. The modelled surface precision in the specifications is set to ±2 mm. Though good modelled precision, it can be noticed that maximum error, representing the point furthest away from the modelled plane, is as much as 16 mm for two targets, both targets well within the recommended scanning range for the system

	Optech. 30 mm point-to-point spacing@60m		
	Standard dev.	Max error	Number of points
Target 1	8	35	59131
Target 2	9	46	13959
Target 3	12	43	1751
Target 4	10	65	512
Target 5	11	37	92

Table 5. Modelled precision for Optech ILRIS-3D.

	Optech. 10 mm point-to-point spacing@60m		
	Standard dev.	Max error	Number of points
Target 1	8	49	307148
Target 2	8	54	72519
Target 3	12	55	9054
Target 4	9	45	2499
Target 5	8	19	156

Table 6. Modelled precision for Optech ILRIS-3D. Only six repetitive measurements included.

In the specifications for Optech ILRIS 3D the single point position accuracy is set to ± 7 to 10 mm. The test shows similar results. The maximum error, however is relatively big, but corresponding to the result for for the relationship between standard deviation and maximum error found for both the Cyrax and the Riegl systems

	Riegl. 75 mm point-to-point spacing@60m		
	Standard dev.	Max error	Number of points
Target 1	20	75	7469
Target 2	19	73	2483
Target 3	20	52	285

Table 7. Modelled precision for Riegl LMS-Z210.

For the Riegl system only three of the test targets could be resolved. The standard deviation indicates a correspondence to the defined range accuracy specified for the Riegl system. The maximum error, however, must be considered quite big even though the relation between the maximum error and the standard deviation is smaller then for the Cyrax and Optech systems.

“True distances” between the test targets were determined and used in comparison to distances decided with each system. This was used in evaluating the systems range accuracy. The result from the Trimble measurements was considered as the “true distances”.

The modelled planes of the test targets for each system were used and between specific positions on the targets, point-to-point distances were recorded. Five different distances between each target were recorded.

	Cyrax	Optech	Riegl*
Target 1 to 2	2 μ μ	2 μ μ	24 μ μ
Target 1 to 3	1 μ μ	10 μ μ	16 μ μ
Target 1 to 4	1 μ μ	9 μ μ	-
Target 1 to 5	2 μ μ	22 μ μ	-
Target 2 to 3	2 μ μ	8 μ μ	7 μ μ
Target 2 to 4	1 μ μ	8 μ μ	-
Target 2 to 5	2 μ μ	20 μ μ	-
Target 3 to 4	1 μ μ	1 μ μ	-
Target 3 to 5	2 μ μ	12 μ μ	-
Target 4 to 5	2 μ μ	12 μ μ	-

*The Riegl system point-to-point spacing was 75 mm at a range of 60 meter.

Table 8. Differences between “true distances” and distances measured with tested systems. The figures are the average of five differences between each target. 30 mm point-to-point spacing at a range of 60 meter.

	Cyrax	Optech
Target 1 to 2	2 μ μ	2 μ μ
Target 1 to 3	1 μ μ	17 μ μ
Target 1 to 4	1 μ μ	12 μ μ
Target 1 to 5	2 μ μ	19 μ μ
Target 2 to 3	2 μ μ	12 μ μ
Target 2 to 4	1 μ μ	10 μ μ
Target 2 to 5	1 μ μ	17 μ μ
Target 3 to 4	1 μ μ	2 μ μ
Target 3 to 5	2 μ μ	5 μ μ
Target 4 to 5	2 μ μ	7 μ μ

Table 9. Differences between “true distances” and distances measured with tested systems. The figures are the average of five differences between each target. 10 mm point-to-point spacing at a range of 60 meter.

A bit surprisingly, it can be noticed that the Optech system has relatively big differences relative to the "true distances" and varies in a strange way over the measured distance. Since the measurements was done between the modelled planes better results was expected. Possibly this has something to do with the system not being perfectly calibrated.

Looking at the Cyrax system it gives very good results, results within the range for the possible accuracy achieved with the Trimble total station.

3.2 How well can the reality be represented?

Evaluation has just started and from what have been noticed all three systems have problems along edges of objects. Looking at the ILRIS-3D data, these edge effects are relatively big, also causing problems in resolving objects. It can sometimes be difficult to see what belongs to what object.

As expected the big spot size of the LMS-Z210 also makes it difficult to resolve small objects from each other.

Cyrax, on the other hand is relative to the other two tested systems extremely good in resolving small details. The small spot size penetrates small openings and registers differences in depth very well.

3.3 Different reflectivity and its influence on measurements

From the test it was clear that the Cyrax system was not capable of measure distances to material with low reflectivity after the recommended range of 50 meter was exceeded. This is probably what could be expected, but we have also noticed at other occasions that our system sometimes looses points within the 50 meter range, especially on objects that seams to have low reflectivity.

At one occasion scanning outside at night-time the system clearly lost points in the very dark areas, but on same material, in lit up parts of the object area, points were registered. This problem is still being investigated and as mentioned in the background and theory part of the paper we are not sure whether the system needs to be re-calibrated.

4. SUMMARY

High-resolution ground based laser scanning systems will probably play an important role in future documentation of buildings. However, it is important to understand where possible erroneous points can be found to be able to evaluate and make use of the resulting point-clouds in a comfortable way.

It has been noticed that all three tested systems gives similar unwanted effects in the resulting point clouds. Two of them are; Strange effects along edges of objects and problems with recording points on certain materials. This is important to have in mind when planning a laser-scanning project. Will the chosen laser-scanning system resolve the details I want to document and what influence will the objects material have on the results?

A small spot size and a system with good range and point position accuracy resolve details best. Not only will this give the most accurate model of the documented object but having a point cloud that has resolved fine details good makes modelling much easier. It is easier to actually see which part of the point cloud should belong to which modelled object.

The work on evaluating high-resolution ground based laser-scanner data at Gävle GIS Institute will continue and our goal is to contribute with results from further evaluations in near future.

5. ACKNOWLEDGMENTS

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COMPARISON OF DIGITAL PHOTOGRAMMETRY AND LASER SCANNING

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KEY WORDS: Laser scanning, calibration, benchmark testing, digital photogrammetry

ABSTRACT:

Terrestrial laser scanners (TLSs) are being used more frequently in cultural heritage recording due to their high data acquisition rate, relatively high accuracy and high spatial data density. In terms of measurement accuracy and quality assurance, performance evaluation techniques and tractable calibration procedures for TLSs are still evolving. This paper reports on three sets of experiments designed to evaluate scanner performance. The first set was conducted in a laboratory environment with the aim to quantify measurement precision as a function of different operational parameters such as scan resolution, pulse mode and range accuracy mode. Results indicate scanner precision was independent of resolution and pulse mode, but dependent upon range accuracy mode. In the second set, a cylindrical object was moved in known vertical increments and scanned at each location to empirically quantify scanner sensitivity. Displacement was estimated by comparing surfaces modelled from the scanner data. Displacements of greater than 8 mm were recovered with an RMS accuracy of less than ± 1mm. The third experiment was measurement of a wooden bridge deforming in response to an applied static load. Bridge deformations estimated by precision digital photogrammetry and laser scanning are compared.

1. INTRODUCTION

Terrestrial laser scanners (TLSs) are being used more frequently in cultural heritage recording due to their high data acquisition rate, relatively high accuracy and high spatial data density. Though parameters vary from instrument to instrument, acquisition rates vary from 1 to 6 kHz, reported ranging accuracy ranges from ±6-25 mm and sampling interval (and hence point density) is generally programmable. These features coupled with the direct measurement of three-dimensional co-ordinates are indicative of the perceived advantages of TLSs over digital photogrammetry.

The issues of accuracy, benchmark testing and calibration of TLSs have yet to receive serious attention. Evaluation of scanner performance by independent organisations has been limited in scope due to the relatively recent emergence of the technology and prohibitive hire and purchase prices. Extensive testing is required not only for quality assurance but also to develop appropriate and tractable field calibration procedures that can be performed prior to commencement of a heritage-recording project. The authors' experiences to date (Lichti *et al.*, 2000; Gordon *et al.*, 2001; Lichti and Harvey, 2002) have indicated that a TLS—a uniform sampling measurement device—is a fundamentally different technology from surveying instruments and digital cameras. As such, a TLS cannot be calibrated or evaluated using standard methods that rely upon the use of precisely measured baselines or target arrays.

This paper presents the results of three sets of tests conducted using Curtin University's I-SiTE TLS. The first tests were performed in a laboratory to assess TLS performance at close range. The aims were to quantify precision as a function of the several different operational modes of the scanner in a controlled environment. The second set of experiments was performed to quantify scanner sensitivity in controlled lab conditions. A cylindrical object was repeatedly scanned after being moved in known increments. The third experiment was comparative testing of precision digital photogrammetry and TLS measurement. This was conducted on wooden bridge undergoing a series of structural load tests. Here, the aim was to quantify scanner sensitivity on a real job site.

2. LABORATORY TESTING

2.1 The Scanner

Curtin University took delivery of its I-SiTE TLS system in early 2002. At the core of the system is a Riegl LMS Z-210 scanner that offers a 336° horizontal field of view (FOV) and an 80° vertical FOV. Range accuracy of the near infrared rangefinder is quoted at ±25 mm in *high accuracy* mode and ±50 mm in *standard accuracy* mode. Maximum range in each case is 350 m and 700 m, respectively. The I-SiTE system offers four preset sampling resolutions, namely *coarse, medium, fine* and *ultra*. The user is able to collect an individual scan of a scene or multiple scans that can be averaged to improve accuracy to ±6 mm (16 scans in high accuracy mode). Also available is the ability to record first pulse or last pulse range measurements.

2.2 The Experiments

The primary objective for the laboratory testing was to quantify the scanner's performance in terms of range precision as a function of the numerous available scanning options. A flat, diffusely reflecting beige wall was repeatedly scanned from a range of 6.1 m. The FOVs were set such that a 1.7 x 1.2 m area was scanned at normal incidence (82° at the extents). The time and room temperature, which remained constant during testing, were recorded at the commencement of each scan.

In total, twenty-one different scanner data sets, each consisting of 16 repeat scans, were acquired. The operational parameters

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of each are summarised in Table 1. Scans 1-4, 13-16 and 16-20 were captured with high accuracy and last pulse (standard parameters) but different resolutions. Four data sets were captured at each resolution to gauge repeatability, though only one ultra resolution scan could be captured with available battery power. For scans 5-8 and 9-12, the pulse mode and accuracy parameters were respectively changed.

Scan Numbers	Resolution	Accuracy	Pulse
1-4	Coarse	High	Last
5-8	Coarse	High	First
9-12	Coarse	Standard	Last
13-16	Medium	High	Last
17-20	Fine	High	Last
21	Ultra	High	Last

Table 1. Scanner Performance Test Cases.

2.3 Experimental Results

Resulting from the testing was a large data set from which reliable precision estimates could be obtained. In total, nearly 2.1 million individual point measurements were captured. For each of the 336 (16 x 21) individual scans and the 21 combined (i.e. mean of 16) scans, a least-squares plane estimate was removed from the data and statistics compiled from the residuals. The mean scan was calculated by averaging the 16 sets of co-ordinates for each point. Some of the findings from these data are presented below.

2.3.1 Individual vs. Mean Scans. For each case, the statistics of the 16 individual and average (mean) plane fits were compared. For all high accuracy mode data sets individual scan precision was ±20-22 mm, while for the mean scan the precision was ±5-6 mm. Clearly, these follow the basic "one over the square root of n" rule from statistics. In a more practical context, this result indicates that a scanner with seemingly coarse rangefinder precision can yield more precise measurements through the exploitation of statistics.

2.3.2 Precision vs. Sampling Resolution. Precision was found to be independent of sampling resolution. Though not unexpected, this result indicates that one need not necessarily acquire an ultra resolution scan in order to attain a desired level of precision.

2.3.3 Precision vs. Pulse Mode Choice. No significant differences in precision were detected between the first-pulse and last-pulse data sets. However, it is acknowledged that a relatively small portion of a wall was imaged at normal incidence. A more complex shape oriented obliquely may produce different results. This is the subject of ongoing testing.

2.3.4 Precision vs. Measurement Accuracy Mode. Operation of the scanner in standard accuracy mode permits measurement of longer ranges (up to 700 m), which is clearly an advantageous feature for larger-scale projects or where site access is restricted. However, the longer range comes at the cost of lower precision. From four standard accuracy data sets, individual scan precision was estimated to be ±35-38 mm, while precision for the mean scans was ±9 mm in all four cases. Clearly there is a degradation of precision, but in this case only by about a factor of 1.7 instead of the expected factor of 2 quoted by the vendor.

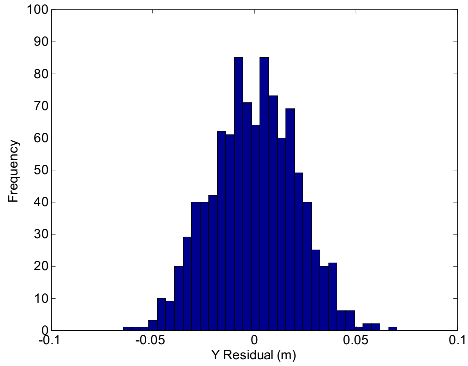

Figure 1. Histogram of Plane Fit Residuals
(Individual Coarse Resolution, High-Accuracy Scan)

Figure 1 is a histogram of plane fit residuals from an individual coarse resolution, high accuracy scan. Figure 2 is a histogram of residuals for an individual coarse resolution, standard accuracy scan. The sample size of each was 999 points and both scans were acquired in last pulse mode. As might be expected, the high accuracy scan histogram follows a Gaussian shape. This behaviour was observed for all high accuracy scans, regardless of resolution or pulse mode choice. Analysis of the standard accuracy histogram reveals a greater dispersion and a possible bias indicated by the minor lobe at 0.05 m. Figure 2 is representative of the other standard accuracy scans. Whatever the mechanism used for deriving longer-range measurements, it is clearly biased.

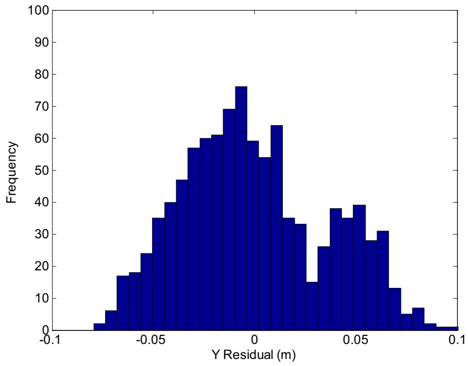

Figure 2. Histogram of Plane Fit Residuals
(Individual Coarse Resolution, Standard-Accuracy Scan)

3. SENSITIVITY TESTING

3.1 Description

As will be described in Section 4, the scanner's ability to sense deformation was tested on a real load-testing project. Laboratory simulations were also conducted to quantify scanner sensitivity in a controlled environment. The assessment was performed by analysing differences in surfaces modelled from laser scanner data rather than on a point-wise basis, as is commonplace in photogrammetric monitoring campaigns.

As pictured in Figure 3, the object used for the testing was a 300 mm diameter, 600 mm long circular-cylindrical bin mounted atop a precision translation stage. The stage allowed application of known displacements. A cylinder was chosen since it closely resembled shape of the wooden stringers scanned during the bridge testing (see Section 4).

Figure 3. Cylinder Displacement Test Set-up.

The scanning geometry and sampling resolution were chosen to replicate (at scale) those of the bridge testing. Five scans were acquired with the bin at the initial (zero displacement) position. The bin was then raised in known increments and five scans were captured at each step. The scanner was levelled and did not move between steps. Each scan consisted of approximately 600-640 points and covered about 40% of the bin's surface.

3.2 Analysis

Deformation analysis was performed by comparing surfaces modelled from the scan clouds. The scan clouds were edited prior to modelling to remove edge effects where the laser beam tangentially grazed the bin and resulted in spurious returns, a phenomenon reported in Boehler *et al.* (2001). This was a necessary process to minimise biases in the modelled surface.

The Maptek Vulcan software was used to estimate a "triangulated surface with second-order least squares trending" (Maptek, 2002). Unfortunately, the on-line help for Vulcan did not divulge the analytical details about the model, which highlighted the need for caution in using "black box" software. The model was applied to each individual scan as well as each scan obtained from the average of the five repeats captured per displacement increment.

Cross-sections were extracted from each modelled surface. Deformation was estimated by measuring the vertical displacement (ΔZ) between the initial and displaced cross-sections. Figure 4 illustrates two such cross-sections. A set of five such measurements was taken from each cross-section and the mean used as the estimated height difference. Table 2 presents the applied and measured displacements and differences for both individual and average scan surfaces.

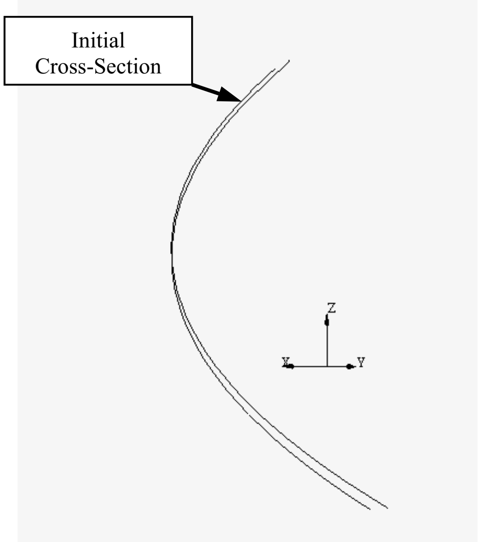

Figure 4. Extracted Cylinder Cross-Sections.

As might be expected, displacements were resolved more accurately from the average scan models than from the individual scan models by a factor of 2.3 (approximately √5, as expected). For the average scan models, the recovery was generally more accurate for larger displacements. Deformations above 8 mm were recovered with an RMS accuracy of less than ±1 mm.

Of concern, however, is the apparent distortion in the cylinder's shape. The cross-sections in Figure 4 are clearly not circular, but exhibit a parabolic shape. This distortion is believed to be due to the non-uniform (i.e. Gaussian) laser wavefront and further highlights the issue of range bias at grazing angles. Nevertheless, the results are encouraging in light of the relatively low precision of the rangefinder (see Section 2).

	Individual Scan		**Mean of 5 Scans**	
Applied ΔZ (mm)	**Observed ΔZ (mm)**	**Difference (mm)**	**Observed ΔZ (mm)**	**Difference (mm)**
1.5	-4.8	-6.3	-1.2	-2.7
6.0	3.6	-2.4	2.2	-3.8
8.0	4.2	-3.8	6.6	-1.4
12.6	8.2	-4.3	12.4	-0.1
16.5	14.2	-2.3	17.0	0.5
25.3	24.2	-1.0	24.6	-0.6
33.5	31.4	-2.1	33.0	-0.5
50.3	57.0	6.7	51.2	0.9
RMS		±4.1		±1.8

Table 2. Applied and Recovered Bin Displacements.

4. BRIDGE TESTING

4.1 Background

Bridge 631 (pictured in Figure 5) spans the Avon River on the Toodyay-Goomalling road some 100 km northeast of Perth, Western Australia. This wooden stringer bridge is constructed chiefly of Wandoo with some Jarrah (varieties of eucalypts) members and is approximately 190 m in length. A stringer is a horizontal member that transfers load to vertical members—see Figure 5. Each stringer was approximately 6 m long with a diameter of 500 mm. The structure has been reinforced with steel beams in several locations where wooden members have rotted or been destroyed by termites. A pre-stressed concrete bridge now takes the traffic load over the Avon River and, at the time of writing (May 2002), dismantling of the wooden bridge was well underway.

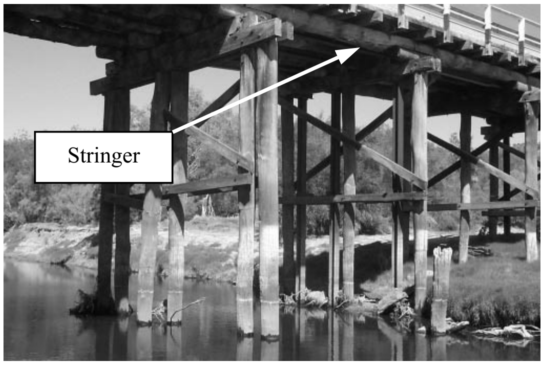

Figure 5. Toodyay Bridge 631.

Prior to disassembly, the wooden bridge was subjected to static load testing on two of its spans in order to determine its strength and load sharing properties. Though this bridge was decommissioned, some 3000 bridges of similar construction exist within the state of Western Australia. Insight into their properties was sought through testing in order to determine how to best maintain such structures.

4.2 Static Load Testing

Static load testing was performed by parking a truck loaded with concrete and steel weights at various locations on the bridge. Linear-variable-differential transformers (LVDTs), digital photogrammetry and TLS were used to measure deflections and load cells installed to measure force. Data from these sensors would be used to infer the bridge's mechanical properties.

Five different loads were applied during testing, with the maximum being 65.75 t. These were placed at various locations (e.g., at mid-span, over columns, etc.). Testing was conducted on two separate days. On day one, a single 6 m-long section was tested with some 95 different load conditions. The time constraints imposed by so many tests dictated that the window in which photogrammetric and laser scanning measurements could be acquired was only 2 minutes.

4.3 Photogrammetric Measurement

An Olympus E20 digital camera (array size: 2572 (H) x 1920 (V) pixels) was used to capture a convergent network of 6 images of the targeted span. Though more would have been desirable, the number of images that could be captured was limited by the time taken to write image data to the camera's memory card. The bridge was imaged prior to the application of each mass to obtain a no-load epoch for deformation analysis. Twenty Gb of imagery was captured on the first day of testing.

More than 200 retro-reflective targets were rigidly fixed to members of the first span. These consisted of a 25 mm circle of retro-reflective film centred on a 50 x 50 mm piece of aluminium angle iron painted flat black. The camera's flash

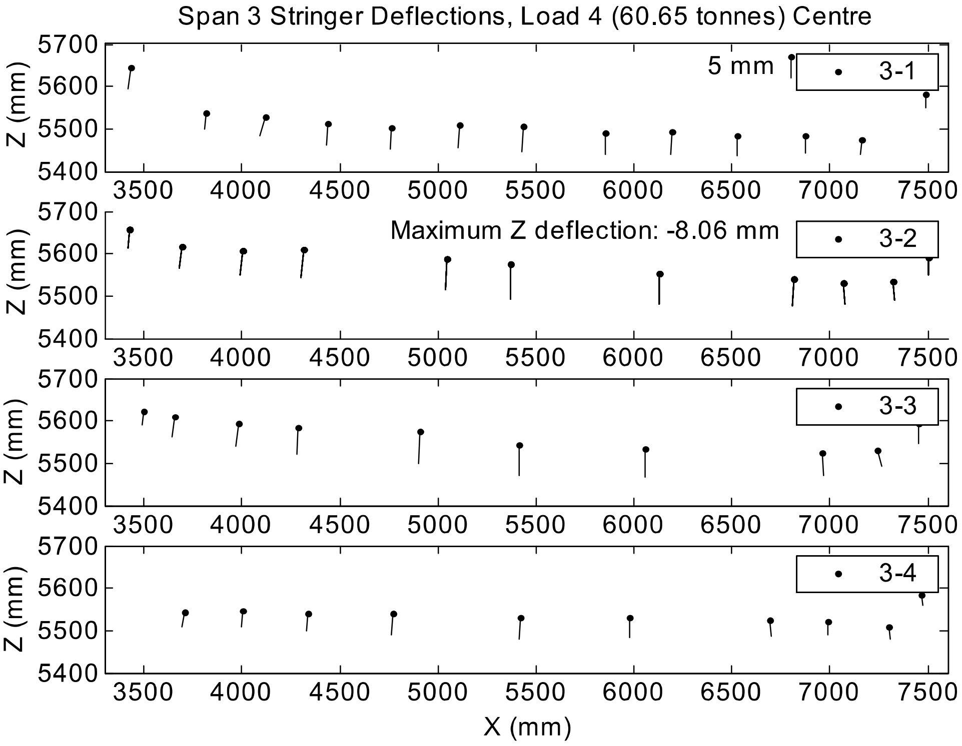

Figure 6. Photogrammetrically-Determined Deformations.

and shutter speed settings were adjusted to obtain optimal target exposure. Twenty-eight targets affixed to three steel beams acted as stable reference points for datum definition. These were bolted to a scaffold structure that was erected independent of the bridge.

4.4 Photogrammetric Deformation Analysis

Image point measurement was made using *Australis* (Fraser and Edmundson, 2000) and free network bundle adjustments were performed using the *FEMBUN* software (Lichti and Chapman, 1997). Points on the steel beams were used to define the datum. Pre-calibrated interior orientation parameters (principal distance, principal point, radial lens distortion and decentring distortion coefficients) were applied as constants. Object point precision in the height or Z dimension—the most pertinent for subsequent structural analysis—was approximately ±0.4 mm for the non-datum points. The 2-minute data acquisition time constraint precluded a realisation of greater precision by capturing more images.

Since all epochs of imagery possessed the same datum definition, deformation analysis was a matter of subtracting loaded co-ordinates from no-load co-ordinates. Figure 6 shows the result of one such comparison. The vectors indicate deflection of the four longitudinal stringers (3-1, 3-2, 3-3 and 3-4) in response to a load of 60.65 t placed at mid-span. As expected, the maximum deflection (-8.06 mm) occurred at mid-span, and defection decreased near the ends where the stringer was supported.

4.5 Scanner Deformation Analysis

Stringer 3-4 was also scanned with the I-SiTE to further ascertain the sensitivity of the scanner for deformation measurement. The scanner remained static throughout the testing. Due to the 2-minute data acquisition window, only a single scan could be captured at each load increment. In light of the results in Section 3 and the small deformations on Stringer 3-4 (–3.3 to –5.2 mm) under the 60.65 t load, expectations about the ability to accurately recover the deflections were low.

The analysis procedure applied for the cylinder testing was utilised for the stringers. Scan clouds were edited to remove spurious returns and then modelled with the “triangulated surface with second-order least squares trending” (Maptek, 2002). Stringer cross-sections were extracted at the locations of the photogrammetric targets to facilitate direct comparison of displacements. Deflections were estimated from the vertical displacement between the no-load and loaded cross-sections at both the top and bottom of each section.

Numerical deflection estimates at eight photogrammetric target locations on stringer 3-4 are presented in Table 3. The scanner displacements measured from the bottom are clearly biased with an RMS error of ±9.1 mm. Displacements measured from the top of the cross-sections are much more encouraging, with an RMS error of ±4.9 mm. In this case, the errors are nearly constant.

Error sources in the displacements include the scanner measurement noise, surface model interpolation error and the shape distortion highlighted in Subsection 3.2. The latter is believed to be dominant error source, particularly at the bottom of the stringers where the shape distortion was clearly evident. Rectification of this distortion is the subject of ongoing research.

CONCLUSIONS

The issues of laser scanner calibration and benchmark testing are important for both heritage recording and metrology applications in order to assure data quality. A series of rigorous tests have been conducted in a lab environment and under real conditions in order to quantify scanner performance. In terms of precision, lab testing indicated that the scanner performed better than manufacturer’s claims, but a bias in standard accuracy range observations was identified.

Further lab testing indicated that, with scan averaging, deflections greater than 8 mm could be recovered with an RMS accuracy of better than ±1 mm. Shape distortion, possibly due to laser wavefront non-uniformity, was found and is likely the dominant error source precluding more accurate deformation estimation. Additionally, more investigation is required into the exact nature of the surface fitting routines that were utilised.

Beam deflections estimated via the laser scanner measurements were biased, but errors were dependent upon the surface used for comparison. Differences between the photogrammetric and the top surface scanner measurements were nearly constant, whereas those from the bottom were not. The previously identified shape distortion as a function of incidence angle is suspected to be the dominant error source and investigations to quantify it are underway.

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Target	Photogrammetric ΔZ (mm)	Laser Scanner ΔZ from bottom (mm)	Difference (mm)	Laser Scanner ΔZ from top (mm)	Difference (mm)
1402	-3.6	-16.0	12.4	-9.6	-6.0
1403	-3.7	-15.0	11.3	-7.8	-4.1
1404	-4.3	-13.6	9.3	-10.4	-6.1
1405	-5.0	-12.4	7.4	-10.4	-5.4
1406	-5.2	-11.8	6.6	-10.8	-5.6
1407	-4.7	-11.0	6.3	-9.4	-4.7
1408	-3.7	-12.0	8.3	-7.6	-3.9
1409	-3.3	-12.6	9.4	-6.0	-2.8
RMS			±9.1		±4.9

Table 3. Stringer Deflections Measured by Photogrammetry and Laser Scanning.

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