Deformation Monitoring Trials Using a Leica HDS3000

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Key words: Laser scanning, deformation monitoring.

SUMMARY

The use of laser scanners for deformation monitoring is a hot topic. Work underway at the University of Nottingham is investigating the application and issues with this.

The paper details trials carried out at the University to investigate the use of laser scanners for deformation monitoring. These trials include monitoring concrete beams in the civil engineering laboratory, and comparing the deformations before and after they were deformed using the laser scanner as well as precise total stations and levels. In addition to this, trials have been carried out on a couple of buildings at the university which are deforming, and looking at the size of cracks that can be detected using such scanners. Further to this, trials have been carried out on a tower block at the university, which appears to have pieces of concrete falling from it. Again the use of a laser scanner could be used to monitor the progress of this. Finally, the reflection and characteristics of a variety of building material have also been investigated.

The following paper will discuss in detail some of the trials conducted in order to assess the accuracy of the laser scanner and hence deduce the possible level of deformations that can be detected.

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1. INTRODUCTION

Terrestrial laser scanning has recently been considered as a possible option for deformation monitoring of structures. This recent attention is because the laser scanner has the ability to generate massive amounts of high resolution 3D coordinated points that globally cover the surface of a structure. The acquisition of this dense geospatial data is very fast, which should provide a better insight into the surface of a structure and how its shape is changing. A structure may be scanned from several locations and when these scans are registered together, they will provide complete surface coverage. To achieve a highly accurate homogenous scanworld from multiple locations, targets are required for the registration procedure. These targets, however, can be positioned away from the structure to tie in the various scans. Although the idea of using the laser scanner is for remote and non-contact operation, for research purposes it is sometimes necessary to place targets on the structural surface to compare the detection of movement against traditional survey methods. Trials have been conducted by Hurst (2005) and Cridland (2004) at The University of Nottingham, to investigate the movement of targets on loaded concrete beams. Proprietary targets were utilised in Hurst’s beam trial, but in Cridland’s test, numerous targets were scanned to assess their effect on a terrestrial laser scanner. The 3D coordinates of the targets were acquired by laser scanner and total station, both before loading, and after failure had occurred. A comparison was then made between the detected movements measured by the two methods. The accuracy of the laser scanner to sense target movement could be evaluated because, for the purpose of the trial, the total station readings were regarded as being the more accurate of the two methods. From Hurst’s concrete beam test, there was a good correlation between the laser scanner and total station measurements. The results from Cridland's trial were reasonable, although the retro-reflective targets were found to cause problems for the laser scanner.

The assessment of structural surface deformations using a raw 3D point cloud would be impractical. Firstly, the ability to precisely repeat the position of each single point in the cloud is low. Secondly, a comparison of every point obtained during each epoch would be time consuming and not statistically significant. To overcome this, the enormous archive of raw 3D point data can be modelled using a digital terrain model and compared between different epochs. Conversely, geometric shapes and planes can be fitted to the raw data points using rigorous algorithms. Gordon et al. (2001) explains that algorithms that rigorously fit shapes to raw points produce a more precise determination of that object than the raw points alone. It is apparent from examination of the Leica Geosystems HDS 3000 technical data sheet that Gordon’s statement is true, as they claim a modelled surface precision of 2mm, as against a single-point accuracy of 6mm (Leica Geosystems website). This surface precision will be of great advantage in deformation monitoring. The reason for this is that a more precise representation of the surface is achieved, thus allowing effective identification of small structural inconsistencies. Consideration of the modelling methodology is essential however, as this will determine the modelled surface precision. Experiments carried out at the University of Curtin (Gordon et al, 2004) have shown the potential of modelling 3D point clouds using simple techniques to improve the accuracy of the laser scanner for deformation monitoring. A concrete beam, timber beam and timber bridge were all subjected to controlled loading. A Cyrax 2500 scanner was used to collect the 3D point data between each load increment. Analytical models were constructed from the raw 3D point clouds to detect and compute the vertical deflection of each beam. The accuracy of the laser scanner was analysed by comparing deflections with photogrammetric techniques. The result of one of the trials was a ±0.29mm (RMS) difference between the two methods (Gordon et al, 2004). The overall outcome of modelling the 3D point cloud in the trials was a significant increase in accuracy when compared the single-point precision of the terrestrial laser scanner.

Structural monitoring using a terrestrial laser scanner will involve taking measurements from surfaces made of different materials. The constituents of a material will inherently affect the energy of the return laser pulse. A material that significantly absorbs the emitted laser pulse will result in a range error, due to an inaccurate time of flight measurement by attenuation of the return signal. The millimetre to sub-millimetre accuracies required for deformation monitoring, will mean that this measurement anomaly cannot be ignored. Lichti and Harvey (2002) have performed a series of tests on a pulsed time of flight measurement system to assess range errors generated from materials possessing different reflective properties. A variety of construction materials such as wood, brick, and stone were scanned at a range of 3m and 53m. Each of the materials was tested with a dry and wet reflecting surface. The properties of the different materials gave insignificant range errors, but apparent changes in material intensity were observed, between samples, and between the dry and wet surfaces. Further trials have been carried out by Cridland (2004), which looked at the return signal intensity of various materials and the scanners ability to detect their movement. The spatial position change of the materials were measured by a Cyrax 2500 laser scanner and Leica total station. Quantification of the laser scanners accuracy to detect movement proved difficult because there was a degree of uncertainty in matching the corners or edges of the materials with a single point.

A successful deformation monitoring scheme using a terrestrial laser scanner will call for measurements of high precision and accuracy. The instrument manufacturers’ quoted precision and accuracy rarely matches the actual capabilities of the instrument. As a result, rigorous calibration procedures are required to determine the true precision and accuracy of a laser scanner. A 52m calibration track line has been used to compare the nominal distance against the actual distance computed by a terrestrial laser scanner. The nominal distance was achieved by the use of an interferometer. This area of research was completed by Shulz and Ingensand (2004), who not only focused on the distance accuracy of a terrestrial laser scanner, but also examined the eccentricity and trunnion axis errors too. Test targets have been installed at the University of Applied Sciences in Germany to investigate the measurement quality of terrestrial laser scanners (Boehler and Marbs et al, 2003). This research has also enabled a comparison between different instrument manufacturers. The distance accuracy, both in the scanning direction and across, was assessed using white spheres as targets. In addition, an appraisal of distance measurement 'noise' was undertaken by scanning plane surfaces of different reflectivity at various ranges.

2. THE LEICA GEOSYSTEMS HDS 3000 LASER SCANNER

The 3D laser scanner system used for all field trials in this research is the Leica Geosystems HDS 3000 (see figure 1). The HDS 3000 laser scanner accompanies two other scanners in the Leica range; the HDS Scanstation and the HDS 4500. Although the Scanstation is the newest of the Leica range, the HDS 3000 laser scanner can easily be upgraded to match its functionality. The HDS 3000 has evolved from the Leica HDS 2500 and Cyrax 2400 laser scanners. The change from Cyrax to Leica HDS has taken place because Cyra Technologies were 'bought out' by Leica Geosystems. Leica Geosystems are a Swiss based company, internationally renowned for the design and manufacture of products for the geomatics industry.

FIGURE 1, The Leica HDS 3000 laser scanner

The Leica HDS 3000 is a high speed, high accuracy laser scanner that combines many different characteristics making it suitable for a wide range of engineering, land and building surveying projects. The HDS 3000 is levelled using a pond bubble and can be forced centred over a known survey point The principal feature that makes this laser scanner more efficient than its predecessors is a maximum 360° horizontal field of view and a 270° vertical field of view. The dual window design- main and upper provides the 270° vertical field of view, with the remaining 45° ground field of view not being scanned. The 360° by 270° field of view allows complete capture of the scene, with fewer instrument set-ups. If only a small object requires scanning, instead of executing a full 360° scan, a ‘window’ facility can be utilised, to select the boundary of the scanning area. This can be carried out in two ways. Using the first method, the horizontal field of view is quickly and easily defined by pressing the ‘Quickscan’ button and rotating the instrument to set the left and right-hand limits of the window. In the second method, the user can image an area of a structure using the onboard digital camera and manually select on the laptop, a horizontal and vertical field of view window. The panoramic digital image mosaic makes it easier for the user to select the exact area that requires scanning (Leica Geosystems website). In addition to this, a 3D point cloud can be viewed using colour from the digital images. This allows for easier interpretation of the features in the point cloud.

The optimal operating range of the laser scanner is 1m to 100m. However, a single point accuracy of 6mm is achieved in the range of 1m to 50m, together with a distance accuracy of 4mm and angle accuracy (horizontal and vertical) of 60micro-radians (Leica Geosystems website). The accuracy of these points is only achievable within that range because of the beam footprint being 6mm at a distance of 0 to 50 meters (Leica Geosystems website). The reflectivity of the surface will also influence the laser scanner system performance. The targets supplied with the laser scanner can be acquired to an accuracy of 1.5mm at a range of 1m to 50m (Leica Geosystems website). These are HDS targets, designed specifically for use with the Leica laser scanner range. The targets are tripod mounted, adhesive planar targets, and magnetic planar targets. A HDS twin target pole also comes with the laser scanner (see figure 2), which is useful for vertical orientation of scans when georeferencing.

The scan density of the point cloud can be manually set using the laptop, with the densest grid being 1mm in the horizontal and 1mm in the vertical. At this maximum resolution, 20,000 points per row (horizontal) and 5,000 points per column (vertical) can be scanned (Leica Geosystems website). The desired point spacing is only achieved by inputting into the software, the approximate range to the feature. This approximate range can be determined using the ‘probe’ function within the software.

FIGURE 2, The HDS twin target pole

The Leica software that is used in conjunction with the Leica HDS 3000 is Cyclone 5.2. This software is designed specifically for manipulation of the point cloud data captured by the HDS 3000. While the laser scanner is in operation, the raw 3D point data is gradually fed into the software, building a model of the structure. The full data capture process can be viewed on the laptop, which ensures the detection of any bad or missing data. The ‘modelspace’ is used to view the 3D point cloud during and after the scanning has finished. Several scans may be acquired from different locations and stored in one project file. The multiple scans can then be visualised, registered, analysed, and transformed into a correct format at a later date using Cyclone.

The registration of several scans will furnish one complete 3D point cloud. Registration is similar to stitching a pair of photos together to achieve a better perspective of a feature. The more stitches, the tighter the fit between the two photos. To register two scans together a minimum of three HDS targets are required to be present in both scans, but these do not have to be positioned on the structure. Three targets are required because the solution of the translation parameters and rotation angles between the two scanworlds requires a combination of six coordinate observations from three non-collinear target points (Lichti et al, 2002). The parameters are estimated by least squares, resulting in the targets in the second scan being rotated and translated to tightly fit with the same targets in the first scan. This theoretical approach is analogous to georeferencing the laser scanner in a local or global coordinate system.

In Cyclone, the targets are 'multi-picked' in the modelspace and given specific names. The software informs the laser scanner of the locations of the selected targets and acquires them to a high order of accuracy. A label and vertex is placed beside and at the centre of each HDS target, respectively. The scans are added to a separate registration facility within the software along with the constraints (targets). The two scans are tied together simply by clicking 'register' and then an error report is delivered to the user. Registering several scans together will involve the same procedure. However, if the final scan does not end with registration of the first scan, then the user should consider the propagation of errors.

It is also possible to register multiple scans together using a technique called point cloud registration. Although this technique is not as accurate as target registration, the ability to carry out a complete targetless operation is of great advantage when scanning unsafe structures. Again, a minimum of three common points in each scan are selected in the modelspace. These points may be features such as well-defined corners on buildings or natural features that are well fixed. For this technique to be successful, it is imperative that the exact same points are chosen in each scan.

3. DEFORMATION SENSITIVITY ANALYSIS

Part of the concrete beam trial involved monitoring the 3D coordinate changes of adhesive HDS targets on a beam. Between each epoch, the expected vertical movement of these targets was a few millimetres. To detect this target movement successfully and with confidence, it was imperative that the sensitivity of the Leica HDS 3000 in detecting the motion of deforming HDS targets was assessed. A subsiding object was simulated at the IESSG to examine the laser scanners aptitude at detecting the vertical motion of two targets. The validity of the quoted 1.5mm target acquisition accuracy was also evaluated.

3.1 Field Work

Two HDS targets were mounted on two stable instrument stands that were levelled using a pond bubble on one of the legs. The instrument stands, approximately 150cm apart, allowed an induced vertical displacement of the targets. Three fixed HDS targets were set up behind the instrument stands- two on tripods and one on a door (see figure 3). The fixed targets were included as a measure of control against the two deforming targets. For all sensitivity analysis tests, the Leica HDS 3000 was positioned central to the two instrument stands, approximately 5 metres away. A Wild NA2 optical precise level with parallel plate micrometer was positioned to the right of the laser scanner. This instrument was used to 'control' the induced vertical increments that the targets were lowered by. The readings from the optical precise level were taken as the truth. Figure 4is a schematic diagram illustrating the relative positions of the instruments and HDS targets.

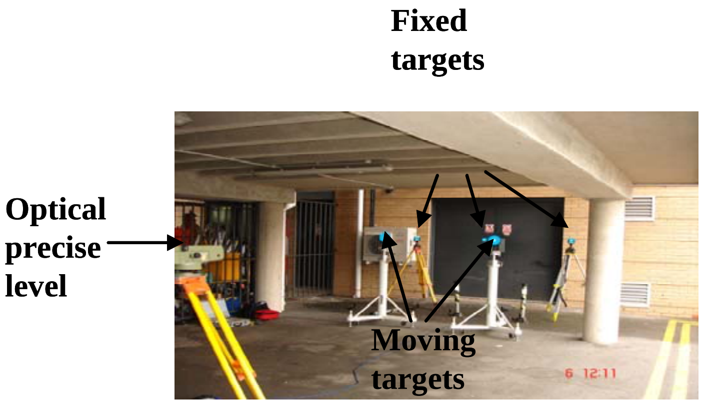

FIGURE 3, Moving targets on instrument stands, fixed targets, and the precise level.

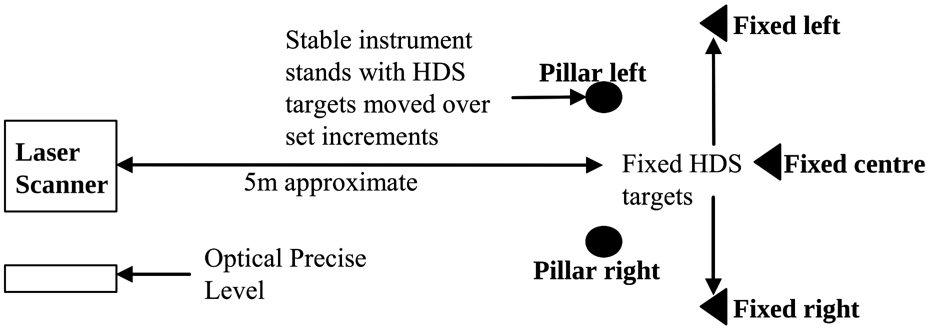

FIGURE 4, The test layout of the deformation sensitivity analysis.

The first deformation sensitivity analysis involved vertically lowering the HDS targets by large increments- 8.5mm, 6.5mm, 4.5mm, and 2.5mm. On the second and third tests, the targets were vertically lowered by small increments- 2.5mm, 1.5mm, and 0.5mm. Before any scanning was executed, the increments were coarsely marked on the vertical translation pole (see figure 5), using a ruler. This was useful in approximating how much the targets required lowering. The first two scans were 'control' epochs, whereby all HDS targets were held fixed in position. The remaining scans were acquired with the targets lowered between each epoch. This gave the perception that an object was subsiding. For each epoch, all targets were scanned with a point cloud resolution of 1mm by 1mm at 5m. The bases of the targets were precise levelled before scanning and between each successive epoch. This was achieved by observing a small precise levelling staff, placed at the base of the target (see figure 5). The use of the laser scanner involved the following steps for each epoch: imaging, scanning, carefully labelling the targets, and acquisition of the HDS targets.

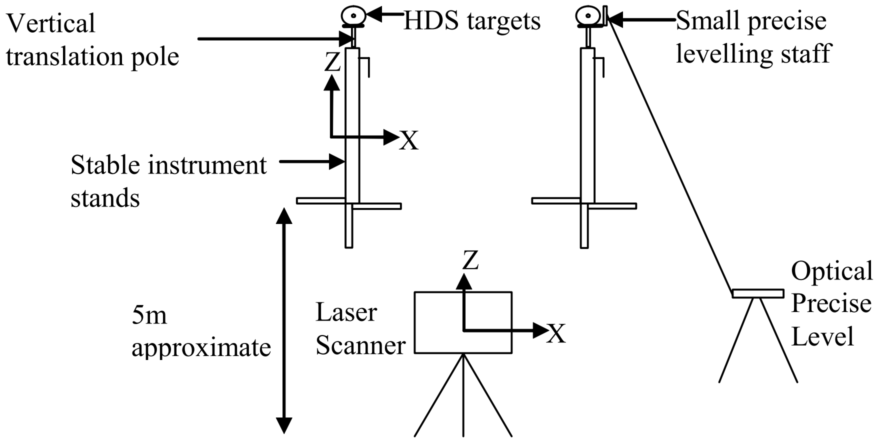

FIGURE 5, The laser scanner, optical precise level, and moving target positions.

3.2 Computation of the Results

The 3D coordinates for the centre of the five targets were extracted by clicking their respective vertexes in the modelspace. A mean set of coordinates was established for the control epoch (0mm increment) using the first two scans. The mean control coordinates were subtracted from the coordinates of the targets from the other scans. The resulting vertical movements detected by the laser scanner were compared to the induced movements measured by the optical precise level. The vertical increments between scans were also computed by differencing the coordinates from each epoch. These detected increments were compared to the vertical increments achieved by precise levelling. Table 1 summarises the 3D movements detected by the laser scanner for pillar right, with the vertical displacement compared to the precise levelling for each scan. Table 2 shows the difference between the mean control coordinates and the coordinates from all other scans for the fixed left target. Table 3 and 4 are the results

FIGURE 6, The origin of the scanner axes and target positions in the point cloud.

	Induced Z (m)	Deformation Vectors (m)			**Difference (m)**	Increments Between Levelling (m)	**Increments Between Scans (m)**	**Difference (m)**
		ΔX	ΔY	**ΔZ**				
Scan 1	-0.0087	-0.0003	0.0022	**-0.0085**	**0.0002**	-0.0087	**-0.0085**	**0.0002**
Scan 2	-0.0152	-0.0002	-0.0018	**-0.0151**	**0.0001**	-0.0065	**-0.0066**	**-0.0001**
Scan 3	-0.0197	-0.0003	-0.0018	**-0.0198**	**-0.0001**	-0.0045	**-0.0047**	**-0.0002**
Scan 4	-0.0223	-0.0002	-0.0020	**-0.0225**	**-0.0002**	-0.0027	**-0.0027**	**0.0000**

TABLE 1, Pillar Right – Summary of large vertical displacements (trial one).

	Induced Z (m)	Vectors (m)		
		ΔX	ΔY	ΔZ
Scan 1	0.0000	-0.0015	0.0027	-0.0004
Scan 2	0.0000	-0.0002	-0.0012	-0.0006
Scan 3	0.0000	-0.0004	-0.0010	-0.0010
Scan 4	0.0000	-0.0001	-0.0015	-0.0011

TABLE 2, Fixed Left – The 3D position uncertainty of a stationary target (trial one).

	Induced Z (m)	Deformation Vectors (m)			**Difference (m)**	Increments Between Levelling (m)	**Increments Between Scans (m)**	**Difference (m)**
		ΔX	ΔY	**ΔZ**				
Scan 1	-0.0025	-0.0002	-0.0010	**-0.0017**	**0.0008**	-0.0025	**-0.0017**	**0.0008**
Scan 2	-0.0041	-0.0004	-0.0017	**-0.0028**	**0.0013**	-0.0015	**-0.0011**	**0.0004**
Scan 3	-0.0046	0.0002	-0.0001	**-0.0028**	**0.0018**	-0.0005	**0.0000**	**0.0005**

TABLE 3, Pillar Right – Summary of small vertical displacements (trial two).

	Induced Z (m)	Vectors (m)		
		ΔX	ΔY	ΔZ
Scan 1	0.0000	0.0002	-0.0012	0.0007
Scan 2	0.0000	0.0002	-0.0006	0.0014
Scan 3	0.0000	0.0004	-0.0009	0.0016

TABLE 4, Fixed Left – The 3D position uncertainty of a stationary target (trial two).

	Induced Z (m)	Deformation Vectors (m)			**Difference (m)**	Increments Between Levelling (m)	**Increments Between Scans (m)**	**Difference (m)**
		ΔX	ΔY	**ΔZ**				
Scan 1	-0.0025	0.0001	-0.0015	**-0.0025**	**0.0000**	-0.0025	**-0.0025**	**0.0000**
Scan 2	-0.0040	0.0000	-0.0029	**-0.0040**	**0.0001**	-0.0015	**-0.0015**	**0.0000**
Scan 3	-0.0045	0.0000	0.0010	**-0.0045**	**0.0001**	-0.0005	**-0.0005**	**0.0000**

TABLE 5, Pillar Right – Summary of small vertical displacements (trial three).

	Induced Z (m)	Vectors (m)		
		ΔX	ΔY	ΔZ
Scan 1	0.0000	0.0010	-0.0022	0.0000
Scan 2	0.0000	0.0006	-0.0021	0.0002
Scan 3	0.0000	-0.0004	0.0015	-0.0001

TABLE 6, Fixed Left – The 3D position uncertainty of a stationary target (trial three)

3.3 Data Analysis

From table 1, the laser scanner has successfully detected the induced vertical displacement (z-axis) of the HDS target. The quality of the detection at pillar right is synonymous at pillar left. The laser scanner has accurately detected the vertical increments between each scan, including the 2.7mm increment. Furthermore, the difference between the detected motion and induced motion was well within the target acquisition accuracy of 1.5mm (Leica Geosystems website). This was probably because the scanning was conducted at such a close range and high resolution. Table 2 shows the z value negatively increasing between each scan for the left stationary target. This will be attributable to settlement of the target and not the laser scanner. Figure 7 illustrates the minor settlement of all three fixed targets, with the most significant movement being in the horizontal (in-plane) x-axis. A small horizontal movement was also detected with the deforming target at pillar left. The horizontal movement appears to decrease in the across scanning direction of fixed left to fixed right.

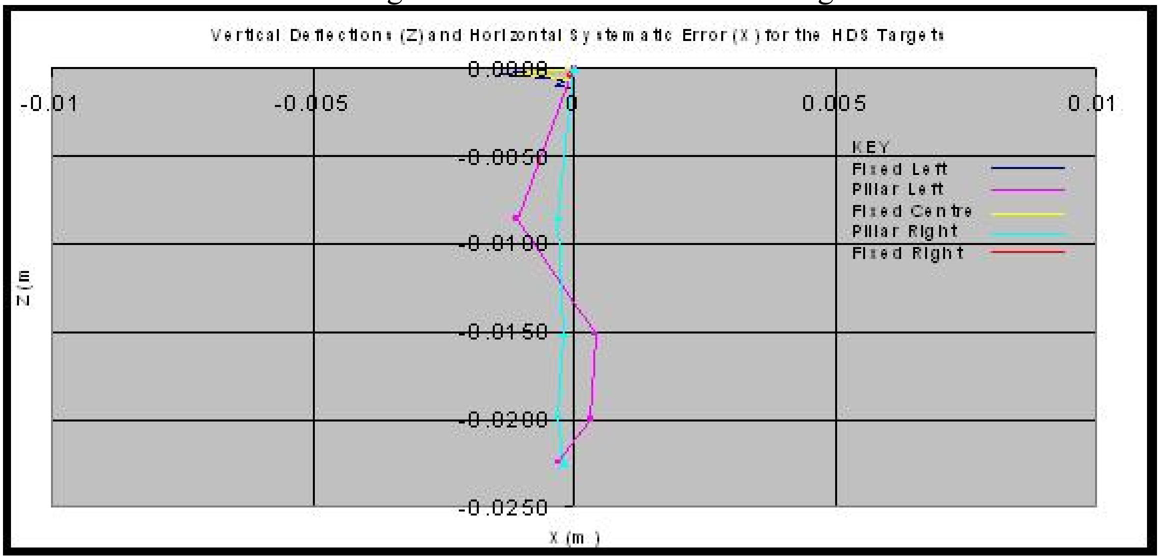

FIGURE 7, The vertical movement of the two HDS targets detected by the scanner.

Although the y coordinate of all targets is fixed between each epoch, the y vector differences appear to be the most significant. This is not targets moving; instead, it is because the y-axis corresponds to the range direction, in which the precision is low. Tables 1 to 6 show the majority of y vector values being negative, indicating a shorter range measurement when compared to the control epoch. A shorter range measurement is usually because of a time delay in the laser pulse, which gives rise to a range delay. The properties of the reflecting surface, incidence angle, and atmosphere are common effects of a range delay. In this field trial, however, these factors did not attenuate the laser pulse's energy since HDS targets are highly reflective; the incidence angle was low, and the laser pulse only passed through a small portion of the atmosphere. The only other factor, which would generate a constant shorter range, is inaccurate measurement of the angles inside the laser scanner. From every y vector anomaly, for all trials, a standard deviation of 1.6mm was computed. This closely corresponds to a close range (<10m) standard deviation of 1.2mm for the HDS 3000, computed during distance accuracy tests, by Boehler and Marbs (2003) at the University of Applied Sciences in Germany.

The second trial involved lowering the HDS targets in small increments. Table 3 shows that the induced vertical displacements were not as successfully detected as in the first trial. Initially, it was considered that this was due to the targets being lowered by very small increments and the laser scanner not having the ability to detect them. However, from inspection of the 2.5mm increment, the detected movement was significantly worse than in the first trial. It was considered that a gross or systematic error had affected the quality of the measurements. A gross error was discovered when looking at the z vector values for all three stationary targets (see table 4). The values were all positive, which increased after each scan, signifying that the laser scanners internal coordinate system was lowering through settlement. The laser scanner tripod was sitting on tarmac that was warm from the day's high temperatures, thus the ground was less stable. In addition, the laser scanner tripod was used in the hot sun prior to the test. The sensitivity analysis was conducted in a cool and shaded environment, therefore the wooden tripod legs contracted, reducing the height of the laser scanner. From the second trial, it was difficult to quantify the laser scanners accuracy in detecting small vertical displacements of 1.5mm and 0.5mm. This is apparent from figure 8, which shows the motion of the fixed targets, approximately the same magnitude as the moving targets. As a result, this trial was repeated to understand the laser scanners aptitude in detecting small vertical displacements.

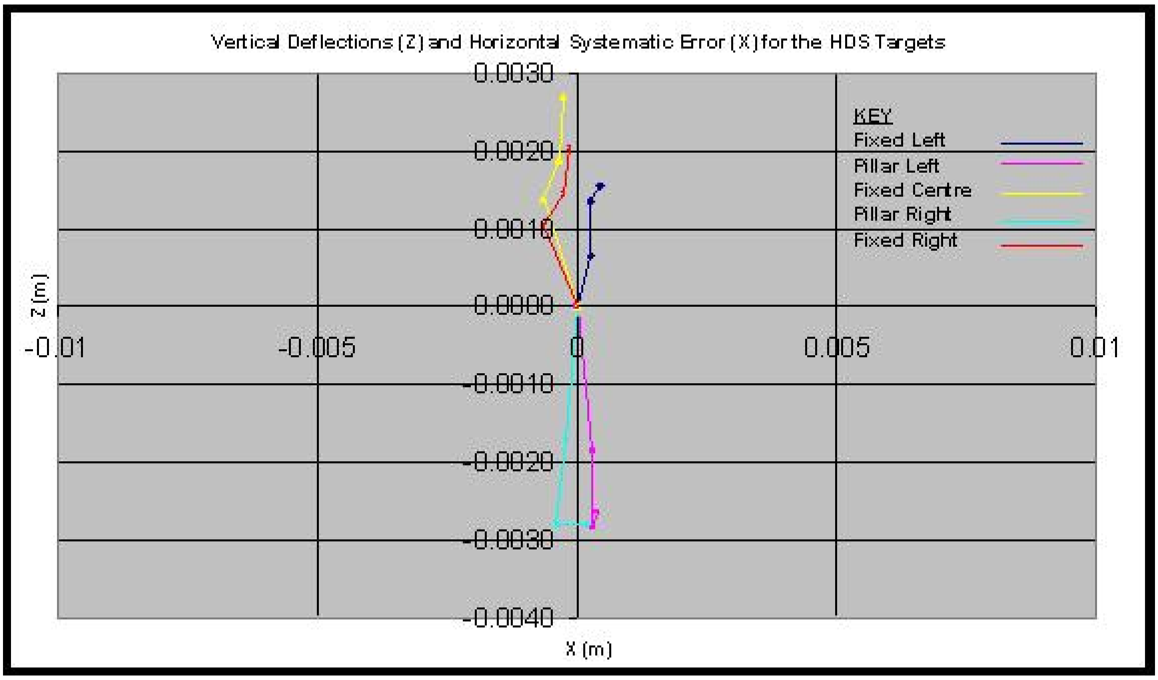

FIGURE 8 ♦ The vertical movement of the two HDS targets detected by the scanner.

Table 6 shows there were no significant movements in the vertical for the fixed left target in trial three. This was also analogous for the other two fixed targets. Due to these insignificant movements, greater confidence could be placed in the laser scanner to detect small induced increments. It is apparent from table 5that all three displacements- 2.5mm, 1.5mm, and 0.5mm, were successfully detected. The difference between the induced motion and detected motion is significantly better than the quoted target acquisition accuracy of 1.5mm (Leica Geosystems website). Figure 9 shows the plotted incremental vertical deflections for the two deforming targets, with a good correlation in their detected movement. Yet again, a small horizontal movement (X) is apparent for pillar left, and for two of the fixed targets, which decreases in the across scanning direction of fixed left to fixed right. This movement may have been caused by dislevelment of the laser scanner and the five targets, as they can only be approximately levelled using a pond bubble.

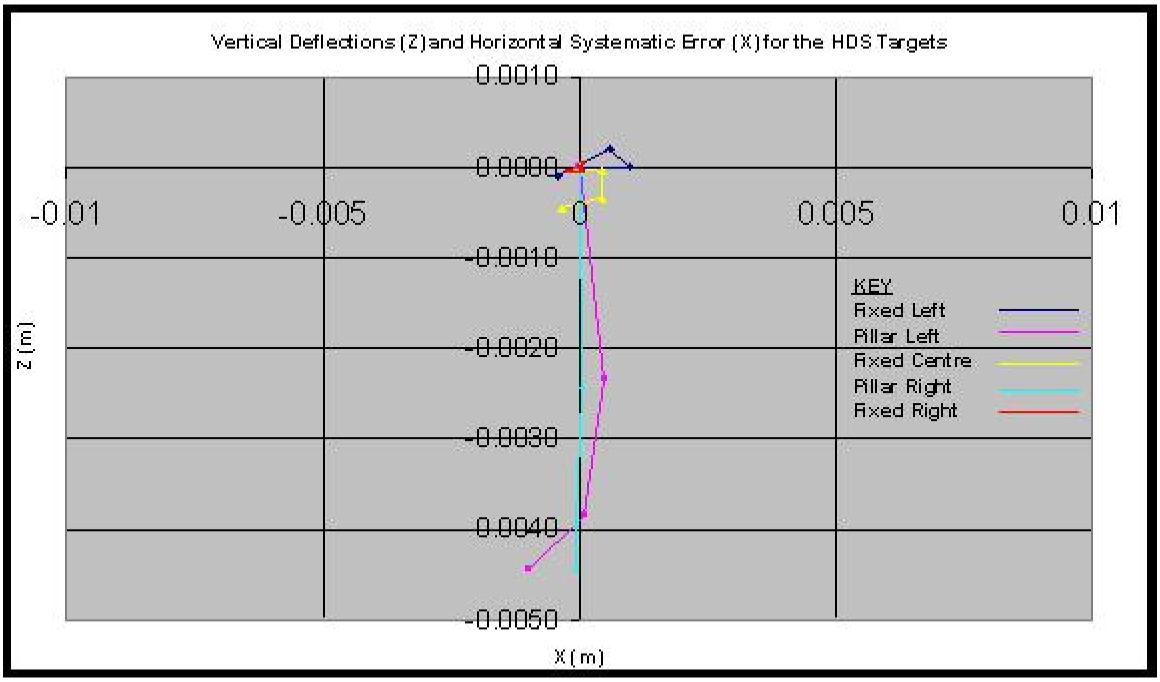

FIGURE 9 ♦ The vertical movement of the two HDS targets detected by the scanner.

CONCLUSIONS

In conclusion, this deformation sensitivity analysis has shown the true potential of the Leica HDS 3000 in detecting the 3D movements of targets to sub-millimetre accuracy. For target positioning, this places the laser scanner in the same accuracy league as the more traditional surveying methods. The induced movement of the targets was accurately established using the laser scanner from a single station set up. Traditional surveying techniques, however, would require two or more station set ups to detect the induced movement, since theses techniques are reliant on the geometry of intersecting rays. With knowledge that the laser scanner can establish the 3D position of a target to high accuracy, it would therefore be advisable to use targets on a deformation monitoring scheme, as verification of the modelled movement. Finally, the positive results from the sensitivity analysis gave confidence that millimetre concrete beam deflections would be detected successfully by the laser scanners acquisition of the targets on the beam.

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