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A Comparison of Close-Range Photogrammetry to Terrestrial Laser Scanning for Heritage Documentation

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Abstract

This paper describes the photogrammetric and laser scan survey of an excavated section of the Laetoli hominid track-way in Tanzania. The survey was designed to allow for comparison to a prior detailed survey of the track-way carried out in 1995, and serves as a means to compare terrestrial laser scanning with close-range photogrammetry as survey methods for heritage documentation.

Each hominid footprint in the track-way was photogrammetrically recorded using a rigorous multi-image controlled configuration. In a separate process a laser scanner was used to scan the entire track-way as well as the individual footprints.

The data for the comparison and track-way / footprint shape assessment were a photogrammetrically generated point cloud and a 3D model (established in 1995 and 2011), as well as a laser scan point cloud acquired in the 2011 survey.

The results showed a high agreement between the laser scan and the photogrammetric data captured in 2011. These two survey processes are entirely independent of each other, the results can be accepted as entirely objective and the excellent agreement between the data can serve as quality control, confirming that the footprint point clouds were captured with an external accuracy of approximately 0.3 to 0.4mm. Standard deviations which are internal precision measures, and typically optimistic, show an individual point accuracy of 0.1 to 0.2 mm. The accuracy for the full laser scan track-way survey was in the order of 1mm.

1. Introduction

During two field campaigns in 1995/6 and 2011 the complete Laetoli hominid footprint track-way (a World Heritage Site in the Ngorongoro Conservation Area, Arusha, Tanzania) 1995/96 and a portion of the trackway (2011) were surveyed as part of the documentation and conservation initiative, conducted by the Getty Conservation Institute, Los Angeles, under the direction of the Ministry of Education and Culture, Tanzania. The principal purpose of these survey campaigns was the detailed documentation of excavated track-way and the individual hominid footprints.

The original survey, of the complete Southern and Northern track-way, was carried out by the Geomatics Department of the University of Cape Town (UCT) in 1995 and 1996 respectively by means of a detailed photogrammetric survey (using both digital and metric film-based cameras), involving three weeks of fieldwork and approximately six months of subsequent data processing.

In 2011 a three metre section of the Southern section of the track-way was re-excavated presenting an opportunity to resurvey the site, for a preliminary assessment of the conservation status. The UCT Geomatics Division undertook the fieldwork for this survey over a two day period (although only four hours of site access was granted to the survey team), using both digital photogrammetric and laser scanning techniques. Independent data processing of both these data sets was completed within one month.

The data gathered not only provides an informative comparison of the track-way and footprint conservation over a 16 year period, but also presents an opportunity to evaluate the appropriateness of survey methods under adverse conditions.

This paper presents the survey methodology used for both the 1995/6 and 2011 field campaigns and discusses the results achieved. In both campaigns close-range photogrammetry in conjunction with a calibration frame was employed, while the track-way was surveyed with a UMK metric camera in 1995 and with a laser scanner in 2011. Comparison is drawn between the results of the various field campaigns (1995/96 against 2011) as well as the results achieved from independent photogrammetric and laser scanning techniques.

2. Close-Range Terrestrial Photogrammetry

2.1. Image Acquisition

The photogrammetric determination of the surface model (or digital terrain model) of the footprint followed rigorous photogrammetric principles in order to achieve highest accuracy and reliability. The photogrammetric method used is briefly described below. Besides the rigorous approach recent fully automated methods developed in the computer vision environment, such as the Bundler and AgiSoft software were also explored but considered not suitable. The reasons for this decision are given in section 4 below.

As for the 1995/96 survey of the individual footprints and in agreement with the state-of-the-art theory of close range photogrammetry, a multi-image/multi-station approach with subsequent bundle adjustment was chosen for the survey. A calibrated camera was used for the photography and a precision control frame was imaged together with each foot print to provide an accurate determination of the camera positions, to provide a scale and to allow for quality control. Multi-image photography is widely accepted as the optimal method in close-range photogrammetry and preferred to stereo photography. The latter is more suited to aerial photography where 60% overlaps are used, while multi-station photogrammetry uses multiple overlaps with up to 100% overlap areas. In case of the footprints, stereo imaging would have been especially inappropriate because of the steep walls of the imprints, which would be poorly modelled from parallel stereo images.

Seven images (there was no time for tripod photography) were captured for each footprint placing the handheld camera in different positions for each image (see Figure 1 below). Some of these images were rotated by 90 and 180 degrees to de-correlate the camera calibration parameters and the orientation parameters.

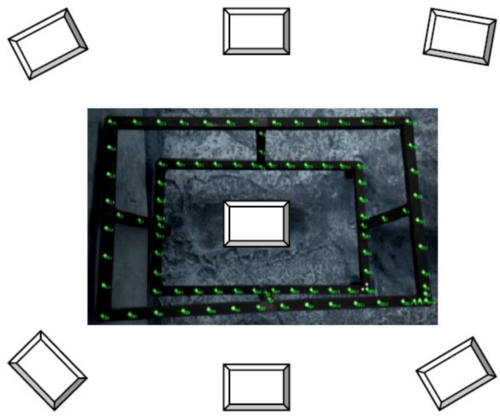

Figure 1 Image acquisition configuration during hominid footprint photography

2.2. Camera Calibration

Camera calibration, i.e. the determination of principal distance (c), principal point coordinates (Xp and Yp) and lens distortion parameters (K1, K2, K3, P1 and P2), is essential for the photogrammetric determination of object points. Without calibration, high accuracy cannot be achieved, especially not for lenses with short focal length, such as wide angle lenses. For the track-way survey with sub-millimetre accuracy requirements, camera calibration was carried out in a laboratory test field at the University of Cape Town and repeated after the field campaign in the same laboratory, in order to check for possible changes of calibration values during transport. No such changes could be detected. In addition to this, the control point frame used for the photography was especially designed to allow in situ calibration checks when processing the acquired images. This was achieved by attaching some 90 control points to the frame, the positions of which were determined by observations with a high precision theodolite and subsequent least squares network adjustment.

The camera-lens combination used for the survey were a Canon Mark II and a Sigma 24- 70mm (1:2.8 EX DG) respectively. The lens was set to a zoom focal length of approximately 38mm and focussed to a distance of about 0.7m, the distance anticipated for the footprint photography. The zoom and focal rings were taped down for calibration and survey.

The calibration method adopted was the "Self-Calibrating Bundle Adjustment" model in applying a free network model. The adopted lens distortion model is ((Fraser, 1992) as cited in (Smit, 1997)):

$$\textit{Radial lens distortion}: \quad d = K_1 r^3 + K_2 r^5 + K_3 r^7 \qquad [1]$$

$$\textit{Decentring distortion}: \quad p = \left(P_1^2 + P_2^2\right) r^2 \qquad [2]$$

A standard deviation of the image coordinates a posteriori of 1.48µm was achieved for the calibration. The calibration results are presented in Table 1 below

Table 1. Camera calibration results

Camera	Canon 5D Mark II
Lens	Sigma 24-70mm f/2.8 EX DG, set to approximately 38mm, focussed to about 0.7m and taped fast.
Sensor size, hz (pixels)	5,616
Sensor size, v (pixels)	3,744
Pixel size, hz (µm)	6
Pixel size, v (µm)	6
Principle distance, f_i (mm)	38.5766
Principal point, x_{pk} (mm)	-0.0188
Principal point, y_{pk} (mm)	+0.0412
K_1	-2.94576e-005
K_2	-9.16435e-008
K_3	+4.02011e-11
P_1	+2.35729e-005
P_2	-6.77383e-006

There is a school of thought in photogrammetry which holds the view that lens distortion for high level amateur digital cameras (such as the Canon 5D Mark II) can be modelled using K_1, P_1 and P_2 only while omitting K_2 and K_3. This was tested but found not to apply for the images captured for the footprint survey.

2.3. Photogrammetric Modelling Process

The photogrammetric survey of the footprints comprises:

- Determination of the camera positions using bundle adjustment and control frame data;
- Extracting of interest points on the object surface for the image matching process;
- Image matching;
- Determination of xyz coordinates of surface point by bundle adjustment.

A set of seven images was taken for each footprint with control frame set up over, but not covering, the foot prints. This image set was processed with in-house software (Smit, 1997). The software comprises of three components, two of which are based on the bundle adjustment, the third one is an image matching algorithm.

2.4. Bundle Adjustment

Because of the prominent role of the bundle adjustment (Brown, 1958) in the determination of the 3D foot print models, the underlying theory shall be explained briefly without much detail.

The bundle adjustment, the workhorse of modern photogrammetry, is a mathematical model, which allows the simultaneous determination of camera position, camera orientation, object point coordinates and camera calibration parameters (see Figure 2 below). Any of these can be either introduced as fixed - if there is prior knowledge of their numerical values - or evaluated as part of the least squares solution. The input can be in form of multi images in any arbitrary configuration, as was the case for the footprint survey.

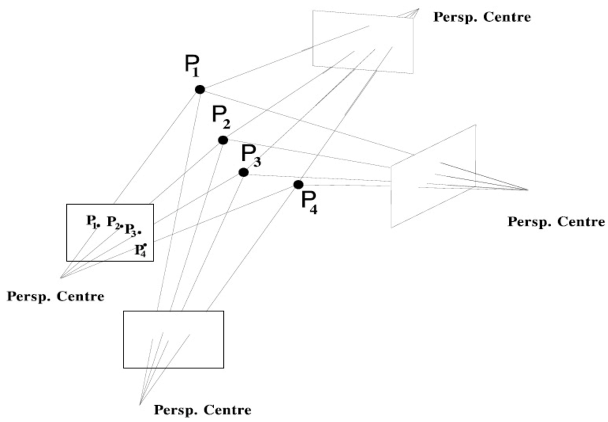

Figure 2. Typical camera configuration of bundle adjustment in close-range photogrammetry

The mathematical formulation of the bundle adjustment is based on the so-called co-linearity condition (McGlone, 1989):

$$x_{ji} + \Delta x - x_{pk} = f_i \frac{r_{11i}\left(X_j - X_{ci}\right) + r_{12i}\left(Y_j - Y_{ci}\right) + r_{13i}\left(Z_j - Z_{ci}\right)}{r_{31i}\left(X_j - X_{ci}\right) + r_{32i}\left(Y_j - Y_{ci}\right) + r_{33i}\left(Z_j - Z_{ci}\right)} \qquad [3]$$

$$y_{ji} + \Delta y - y_{pk} = f_i \frac{r_{21i}\left(X_j - X_{ci}\right) + r_{22i}\left(Y_j - Y_{ci}\right) + r_{23i}\left(Z_j - Z_{ci}\right)}{r_{31i}\left(X_j - X_{ci}\right) + r_{32i}\left(Y_j - Y_{ci}\right) + r_{33i}\left(Z_j - Z_{ci}\right)} \qquad [4]$$

With

x_{ji}, y_{ji}	image co-ordinates of point P_j on image i
f_i	principal distance of camera k at station i
x_{pk}, y_{pk}	principal point co-ordinates of camera k
Δx, Δy	correction terms allowing for systematic errors
$r_{11i} \ldots r_{33i}$	elements of rotation matrix of image i
X_j, Y_j, Z_j	object point co-ordinates
X_{ci}, Y_{ci}, Z_{ci}	perspective centre co-ordinates

In the case of the footprint survey, the bundle adjustment was used to determine both, the camera position (exterior orientation) and the object point positions, i.e. the surface points, as it is integrated into the image matching solution (Smit, 1997).

2.5. Interest Point Extraction and Image Matching

Points of interest, i.e. points representing texture in the images of the footprints, are located in one of the acquired images in a fully automated process. The location of these points involves a high pass filter of the image, which serves to enhance the high frequency components in a fairly uniform image. The high pass filtered image is then convolved with a kernel designed to extract gradient changes above a specified threshold level.

Once the interest points have been determined by convolution in the x- and y- directions, they are combined (vectorised), thinned out (Förstner thinning operator) and located to sub-pixel accuracy with the method of 'preservation of the moment'.

Points corresponding to the extracted points of interest in the remaining images are then extracted. The image point coordinates are required to obtain the object space coordinates (XYZ) for the points of interest in a subsequent space intersection program (bundle adjustment). The identification and the determination of such conjugate point positions in terms of image coordinates is referred to as image matching.

The image matching process employed for the footprints relies on a least squares solution with geometric constraints, where matching image points are determined together with the object space coordinates of the corresponding object points. All software employed for interest point extraction, image matching and bundle adjustment was developed in-house.

The number of points found in this automated approach was about 50,000 for each footprint for all data sets. The bundle adjustment result showed image coordinate precisions of 2μm, again confirming the overall high accuracies of the integrated survey operations.

2.6. Results of the Photogrammetric Process

The results of the photogrammetric process are a point cloud of thousands of surface points for each footprint. The footprint point clouds were captured with an external accuracy of approximately 0.3 to 0.4mm. Standard deviations which are internal precision measures, and typically optimistic, show an individual point accuracy of 0.1 to 0.2mm.

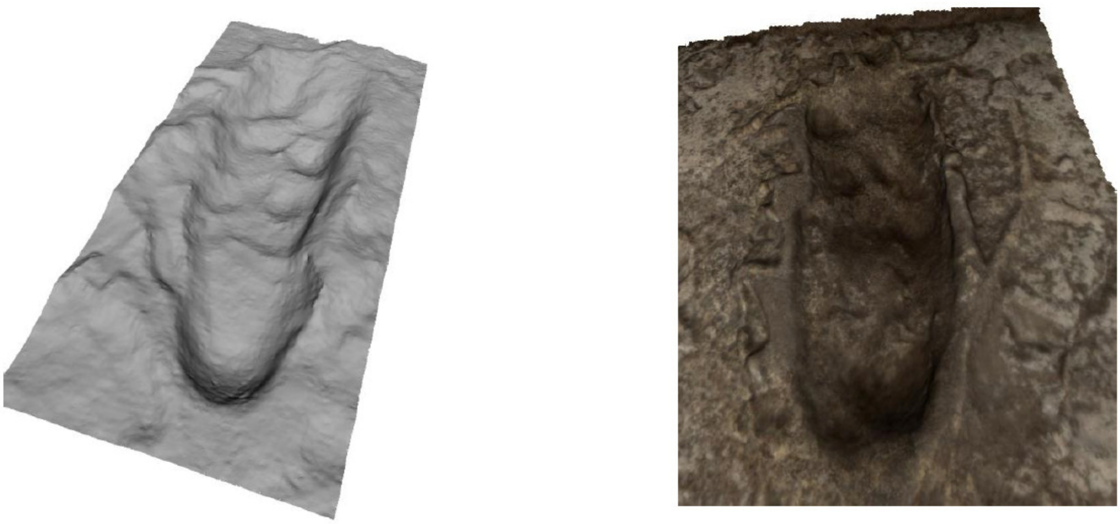

Figure 3. Un-textured (left) and textured (right) models of G23-28 and G23-27 respectively.

These point clouds are then connected to form complete (un-textured) surfaces and photographs are draped over the surface in a final step to create a textured model. Examples of screen prints of an un-textured and a textured model are given in Figure 3.

2.7. Comparison of 1995 and 2011 Footprint Survey Results

The objective of the photogrammetric survey was to establish if any deformation had occurred in the footprint surface shape since the re-burial of the track-way in 1995. This comparison was achieved by geo-referencing the footprint point clouds generated during the 1995 and 2011 epoch to each other and by then subtracting the elevations of corresponding points.

It is important in this context to note that there considerable differences in the image resolutions of the two epochs. The camera used during the 1995 photography was a Kodak DCS200, at the time one of the most advance cameras of its kind. The resolution of the camera was 1.5 Mega pixels, compared to the 21 Megapixels of the Canon 5D Mark II used for the 2011 survey. This resulted in different resolutions for the DTM which necessarily leads to differences between the two data sets, as demonstrated below, even if there are no changes in the surfaces.

8	10	9	10
8	7	10	9
10	8	10	8
9	10	9	10

9

-1	1	0	1
-1	-2	1	0
1	-1	1	-1
0	1	0	1

The simulated example above demonstrates the effect of different DTM resolutions on surface differencing. **Left**: a 4 by 4 raster of DTM cells with elevations values in mm is assumed. **Centre**: the same area covered by only one DTM cell with the correct mean of 9mm. **Right**: the result of differencing the two DTM resolutions. The simulation shows differences of 1 to 2mm occur although the surface is identical in this simulated area. This phenomenon partly explains the differences between the two epochs as shown in Figure 4. The differences are the result of random observation errors. Grey areas in the images indicate sections where no data could be determined during either the 1995 or for the 2011 survey. These are the result of the absence of well-defined features in certain parts of the images.

Figure 4 is a sample diagrammatic representation of the differences between the 1995 and 2011 surfaces. The diagram was produced with Geomagic software. Warm colours (yellow to red) indicate that the 1995 surface is above the 2011 surface, while cold colours (cyan to blue) indicate the opposite. Inspection of the difference diagram (deviation distributions) and the corresponding difference histogram shows convincingly that deviations are random and the result of unavoidable observation inaccuracies combined with the effect of the different resolutions, which are also random in nature.

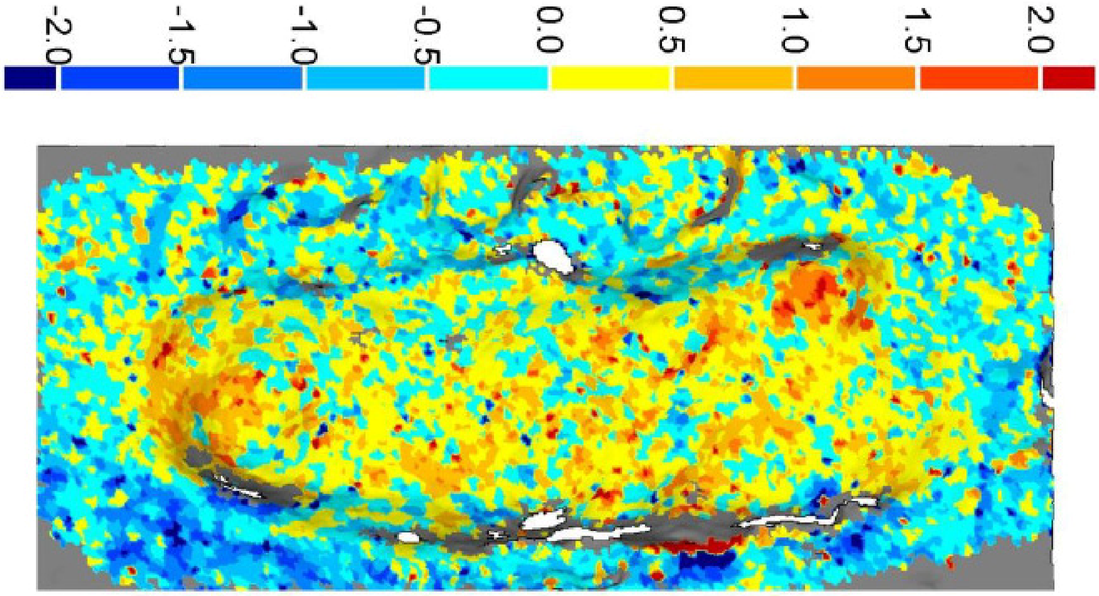

Figure 4. Deviation distribution (in units of mm) of G23-27

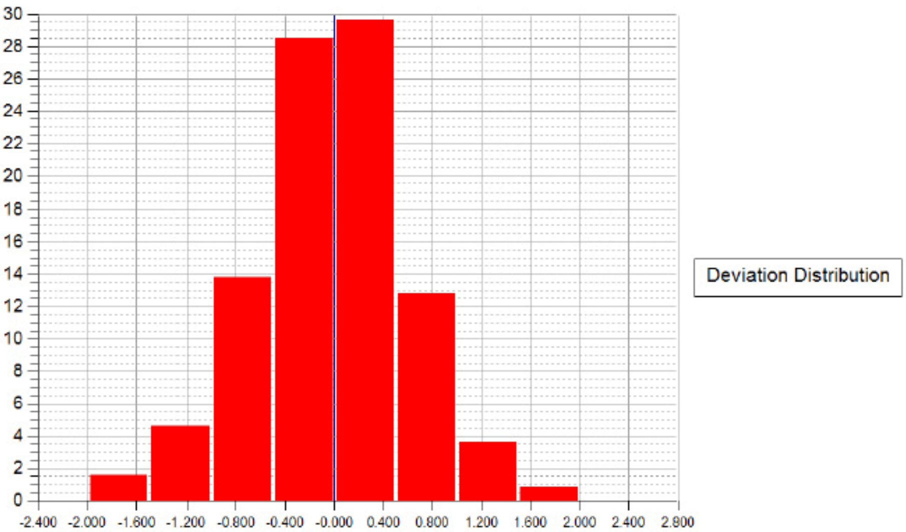

Figure 5. Histogram of deviation distribution of G23-27 (units of mm along the horizontal axis)

The histogram (Figure 5) shows the frequency of differences between the two surfaces grouped in classes of 0.4 mm class interval. The histogram shapes clearly reflect the typical bell curve of the normal distribution without any bias or skewness. This is characteristic for observations and a confirmation that the differences are not systematic.

3. Terrestrial Laser Scanning of the Track-Way

In order to establish if the overall track-way, as opposed to individual footprints, has suffered deformations since its reburial in 1995, the original contour map produced in 1995 and the laser scan data acquired in 2011 were compared. The original contour map was produced using a conventional photogrammetric mapping approach on a Zeiss Jena analytical plotter. Images were captured on glass plates with the metric Zeiss Jena UMK10 camera. The contours were hand drawn following the standard procedure for photogrammetric mapping in the 1990's.

For the 2011 survey, a Leica HDS 6100 laser scanner was employed. The instrument was set up in four positions around the exposed site as shown in Figure 6. The scans were executed in the highest possible scanning resolution. The four scans were combined by Iterative Closest Point (ICP) registration (Besl and McKay, 1992) into a single point cloud of about 6,000,000 surface points. The points were converted to a surface mesh (see Figure 7 and Figure 8) using a Poisson algorithm resulting in an estimated accuracy of 1 to 2mm for surface points.

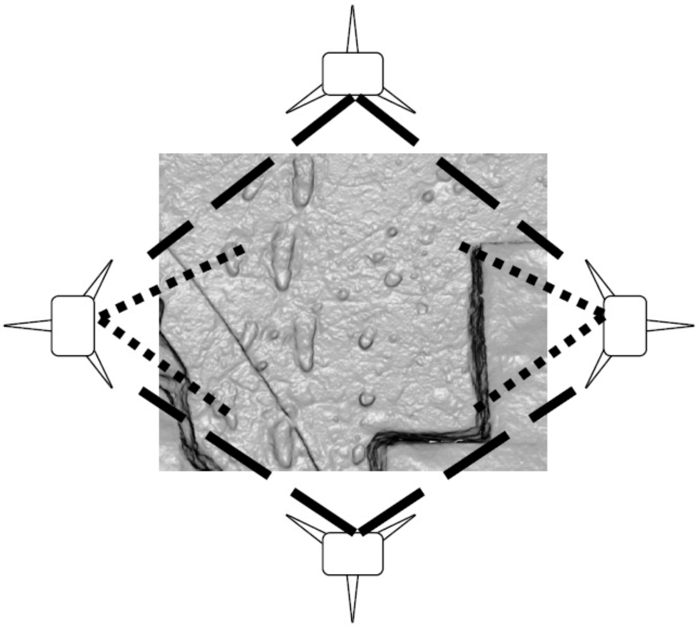

Figure 6. Laser scanner set up positions during track-way survey

The difference in data acquisition techniques 1995 and 2011 caused some complications for the comparison and resulted in a "Zebra pattern" (Figure 9) when displaying the differences between the two surface models. When manually producing contours, using an analytical photogrammetric station on terrain with a flat gradient, as was the case for the foot prints for the 1995 campaign, small operator-specific errors in positions of the contours are unavoidable. These will result in contours of the correct shape being displaced by small amounts placing the contours marginally above or below the terrain, as indicated in Figure 9. The lateral displacement of the contours between the 1995 (analytical photogrammetry) and 2011 (laser scans) for the track-way was in the order of 1 to 2mm. The two surveys were of similar accuracy.

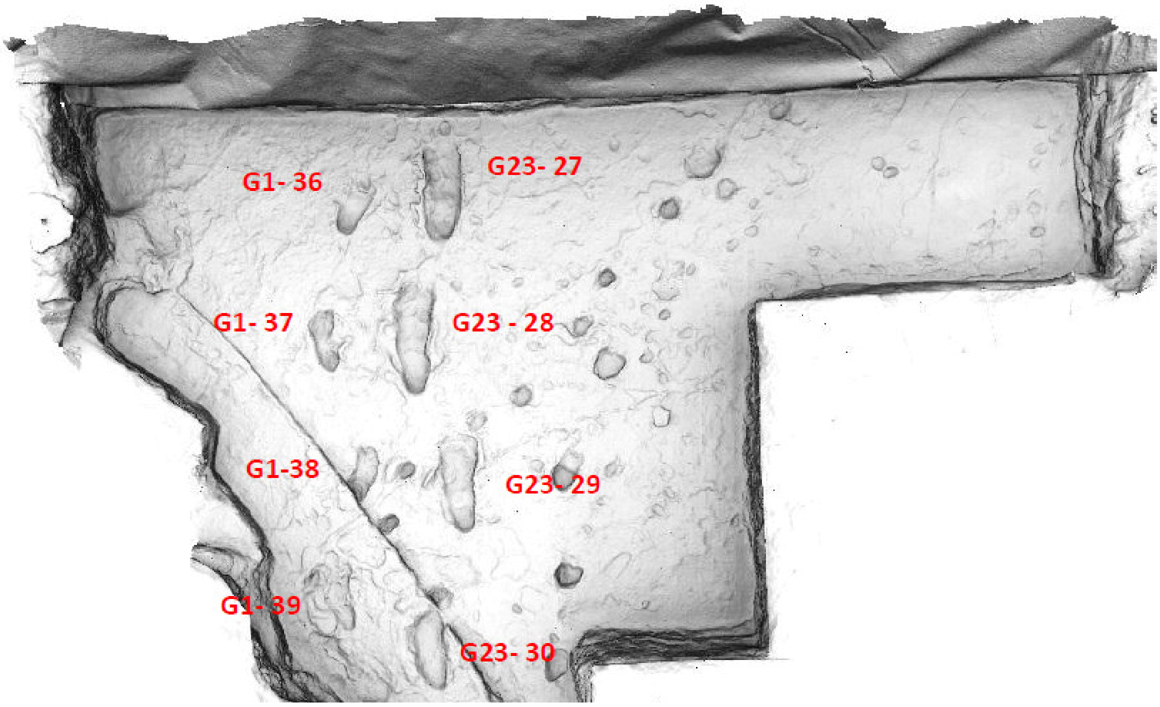

Figure 7. Un-textured model of the exposed track-way section as derived from laser scanning showing foot print labels

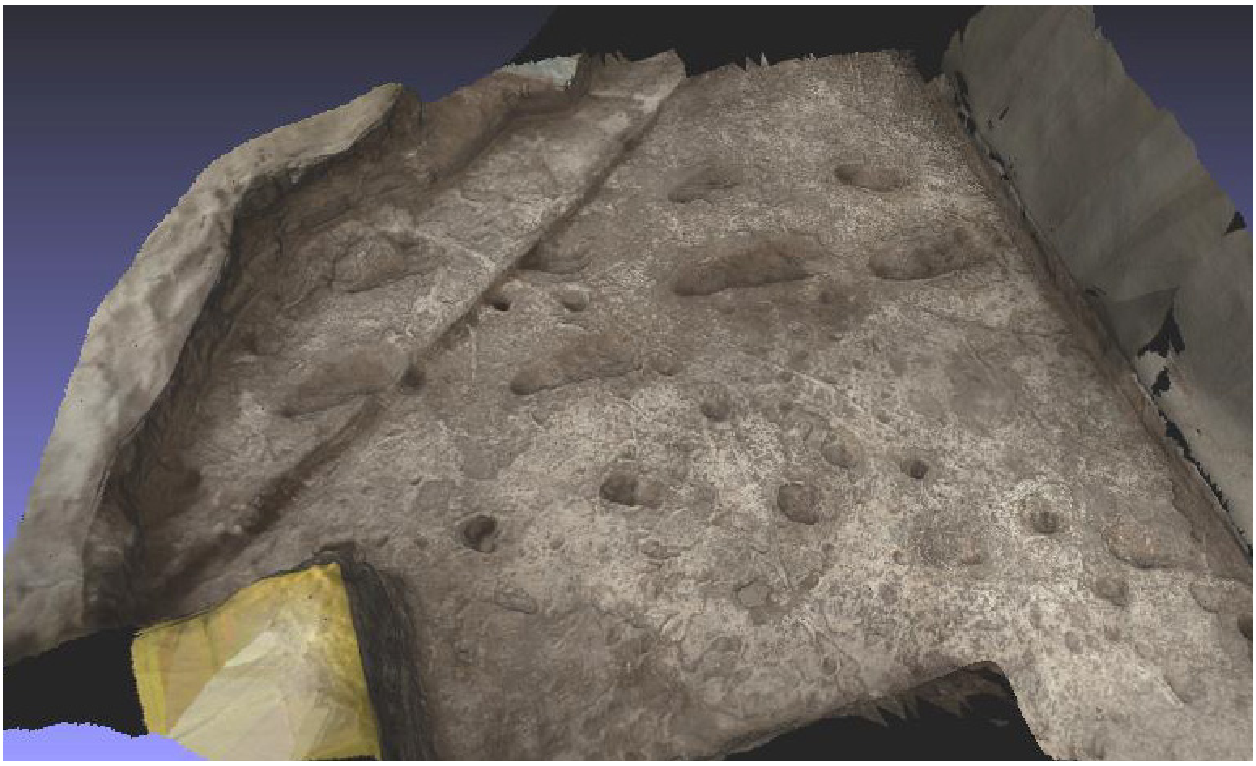

Figure 8. Textured model of the exposed track-way section from laser scanning

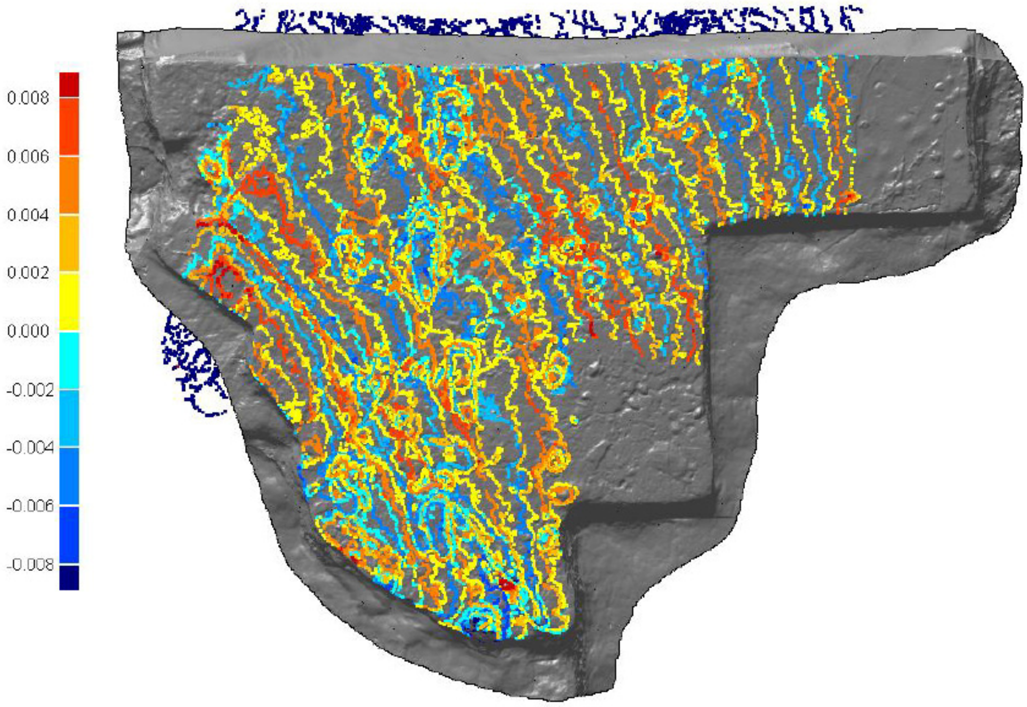

Figure 9. Comparison of 1995 versus 2011 track-way surfaces (units in mm)

The comparison shows a “Zebra stripe” pattern which arose as a result of the lateral displacement. It is important to note that this does not reflect a systematic (wave shape like) deformation of the surface. But that this is merely a computational artefact, which does by no means indicate that the surface suffered deformations (see Figure 10 and Figure 11).

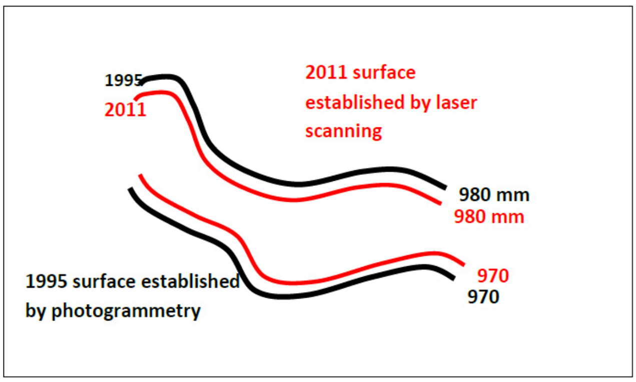

Figure 10. Plan view of a simulated contour displacement between 1995 and 2011

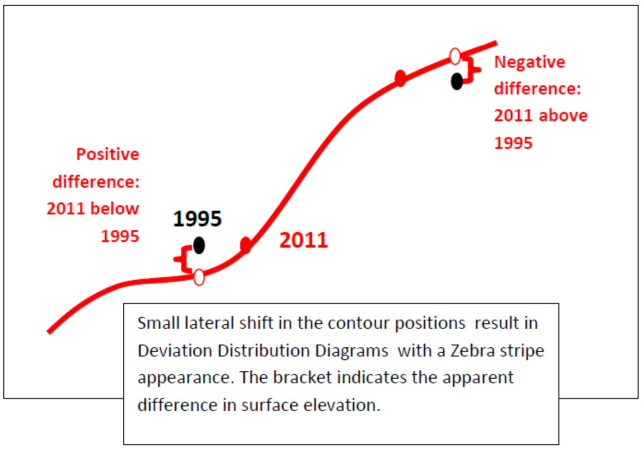

Figure 11. Vertical section through simulated surface

4. Structure-from-Motion Methods

In recent developments an interesting approach to 3D Modelling has emerged from the computer vision community. This method is referred to as "structure-from-motion" and implemented in a number of software packages such as Bundler and AgiSoft. Structure-from-motion software is fully automated and based on bundle adjustment and image matching algorithms. It has the advantage that its use does not required any skills or photogrammetric knowledge and that its application can be learned within a few minutes. The method generally produces good looking textured models and is ideally suited for models which do not have to be metrically accurate. The method is a computer vision approach with an emphasis on appearance and high quality rendering, as opposed to a photogrammetric method with highly reliable, metrically correct outcomes. Its use is extremely easy. All it requires is that the user uploads multiple images of an object and the results are produced fully automatically without user interaction. The principal disadvantages of the technique are that the mathematical process is not transparent and not enough research has been done or published as yet to be confident about metric accuracy and reliability of this approach.

The photographs of the track-way were entered into AgiSoft and results were good in appearance, however, the accuracy could not be assessed, apparent distortions were observed and it was decided not to use structure-from-motion software and instead rely on the results obtained using established photogrammetry combined with laser scanning for the modelling of the footprints, while the track-way surface was modelled from laser scan data only.

5. Conclusions

Inspection of the results showed that the photogrammetric survey as well as the laser scans were successful and provided reliable data. This could be concluded in view of the good agreement between the laser scan data and the photogrammetric results of the 2011 survey on the one hand and the 1995 photogrammetrically established surface models on the other. Such agreement over the entire area could not be coincidental. Accuracies achieved were in the order of 0.2mm for the individual foot prints and 1mm for the complete track-way. Differences between the surfaces were of the magnitude of these accuracies and can therefore be explained as random and not as an indication of any systemic deformations of the footprints or the track-way surface.

When making a comparison of the merits of photogrammetry versus laser scanning, as a suitable means of heritage documentation, one is invariably faced with decisions concerning: speed of fieldwork data acquisition, accuracy, the need for permanent records, portability, field conditions, etc. The growth and popularity of laser scanning in many aspects of surveying has for some time seen photogrammetric techniques lose favour, as laser scanning is perceived as quicker and easier and more accurate. This study has demonstrated that photogrammetry still has a part to play in precise documentation and that the two techniques should be considered complementary rather than in competition.

In a documentation campaign such as was conducted for this project in 2011, under adverse site conditions and severe time constraints, it was precisely the combination of techniques which allowed for a highly accurate and detailed survey to be conducted. Both digital photogrammetry and laser scanning proved their worth in different aspects of the survey: photogrammetry being the more suitable technique for a detailed survey of the individual footprints and laser scanning providing an ideal solution for the track-way survey.

6. Acknowledgements

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