Development of low cost 3D soil surface scanning for physical modelling

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ABSTRACT: 3D scanning is becoming increasingly commonplace in everyday life, but its potential may be yet to be fully exploited in geotechnical research. Key barriers to its use include issues such as the high cost of the hardware required, the need for specialist or custom built software for processing the 3D scan data and challenges in visualising the final 3D scan. This paper describes the development of a low cost soil surface scanning system that can create a 3D representation of a physical model's surface geometry accurate to within +/- 0.5 mm. The system is based around a low cost commercially available scanner which is easily deployable and provides rapid output in an integrated 3D model which can be easily visualised and interrogated. Measured physical model surface geometry can also be easily transferred into numerical modelling software to allow complex surface boundaries to be modelled. The scanner output allows detailed analysis of surface deformations such as the measurement of features of interest, generation of cross-sections of physical models and the calculation of areas and soil volumes.

1 INTRODUCTION

The increased use of 3D Finite Element Analysis (FEA) in geotechnical research for large displacement applications such as seabed ploughing (Lauder et al, 2013) has generated a need for accurate verification using physical modelling. In these cases, the deformation of the soil surface is of the utmost importance for accurate representation of boundary conditions and localised effective stress changes especially in low effective stress conditions (e.g. near surface ploughing operations). Other potential examples of physical modelling where this is important include iceberg scour (Arnau & Ivanovic, 2015) and displacement auger piling (Al-Baghdadi et al, 2015).

Currently in physical modelling the surface deformation is either measured by hand or at key locations using displacement transducers. However, this can limit the amount of information available when the aim is to compare the model with a 3D FEA prediction. A 3D soil surface scanner presents the potential for comparing the entire physical model surface deformation with the predicted surface profile extracted from the FEA. Contactless measurement is particularly useful in applications such as this where the soil surface is susceptible to disturbance or in scale model applications where the accuracy of surface level determination may be important.

1.1 *Overview of Scanning System*

The scanning system described in this paper has been developed to facilitate comparison of both 1G and centrifuge models of offshore seabed ploughing with the output from new meshless FEA software being developed at Durham University using the Material Point Method (MPM). The scanner has since been found to be applicable to a wide range of physical modelling applications. The scanning system is based around a commercially available 3D scanner (developed for 3D printing applications) which is low cost and widely available.

1.2 *Previous Scanning Systems*

Previous scanning systems used in geotechnical research have been developed based around the principle of using a line laser projected onto the soil surface from a moving platform and triangulating the surface profile using still images taken by a fixed camera in a known position (Ivanovic et al, 2011; O'Neill et al, 2009). These systems typically have a resolution of 0.5 mm and can scan objects with widths of up to 1 m.

However, the output of these systems is a series of cross sectional profiles and combining these together to make an easily visualised model can be a time consuming process. The system also has to be spe-

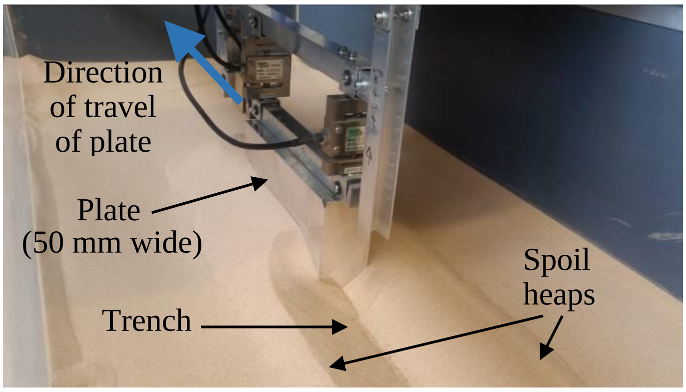

Figure 1. Experimental setup for ploughing aluminium plates as simple cable plough analogues.

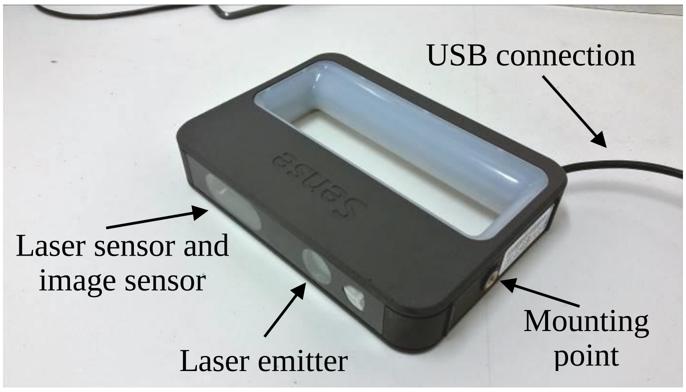

Figure 2. 3D Systems Sense™ 3D Scanner.

cifically built to suit the geometry of the model in question and requires a linear actuator to move the laser, regardless of the size of the model. Image processing is also required to extract the surface profile from the captured images.

The scanner system developed at University of Dundee aims to overcome these challenges and make 3D scanning more widely available in geotechnical physical modelling.

2 SCANNER DEVELOPMENT

The purpose of developing the scanner was to provide a way to capture the surface geometry of a sand bed which was to have aluminium plates of varying widths (designed as simple cable plough analogues) ploughed through it (post ploughing). Simple rectangular plates were used as they are easier to model in the numerical modelling techniques currently being developed. The plates were fixed to a load cell arrangement to maintain constant embedment depth in the sand bed whilst they were ploughed, generating a trench approximately 1.5 m long behind them (see Figure 1). The equipment design is based on a modified version of that previously developed by Lauder et al (2012).

2.1 *Scanning Unit*

The system is based around a Cubify Sense™ 3D Scanner made by 3D Systems Inc. This is a low cost commercially available unit initially designed for the home 3D printing market, costing less than £300 (€400) which has since been used in a number of fields and industries.

As shown in Figure 2 the unit measures 178 x 129 x 33 mm and on the base it has a universal camera thread for mounting. The front face of the scanner contains a laser emitter, laser sensor and image sensor.

The scanner is connected to a computer by USB whilst scanning and is controlled using Sense™ (v2.0) software. It operates by projecting a dense, irregular array of individual laser points onto the soil surface which allows a point cloud to be generated by triangulation from the laser sensor. Based on this point cloud the scanner can track its own position in real time relative to the soil surface allowing the scanner to be moved during scanning if required. This means that no control markers or lighting systems are required to capture the surface, as the location of the scanner itself (principle point) is continually updated based on its position relative to the known point cloud determined so far.

Once the physical model surface has been captured, the software automatically processes the point cloud by fitting a mesh surface with up to 250,000 nodes through the measured point cloud in order to provide the best possible fit that provides a 3D representation of the surface. The mesh surface is then exported as either STL or OBJ file types which can be readily imported into standard engineering 3D modelling software such as AutoCAD or can be 3D printed directly if required.

In order to deal with scanning areas of different sizes, the density of the mesh nodes is automatically adapted in terms of the spatial (x, y) resolution to suit the requested scan dimensions. Consequently, the level of detail captured is reduced for larger scan areas. In these circumstances it is advisable to scan larger models in several smaller scans and to recombine these into a single 3D model.

To investigate the effect of selected scan area on the resolution and accuracy of the scanner, a flat machined metal surface was scanned in each of the available modes; small, medium and large. The spatial resolution of the scan output mesh and the maximum vertical deviation from the expected flat surface are summarised in Table 1. Additionally, no variations in spatial or distance measurements due to temperature changes during scanner sensor warm-up were observed.

Table 1. Resolution and accuracy of the scanner for varying scan area modes.

Scan area m^2	Spatial resolution (x, y) mm	Vertical accuracy (z) mm
0.09 (Small)	1.0	± 0.40
1.00 (Med.)	2.6	± 0.55
9.00 (Large)	5.2	± 0.65

2.2 *Mounting and Alignment*

To correctly centre the scans on the physical model soil bed it is important to understand the reference system of the scanner unit. Tests showed that the origin of the 3D scan output is directly centred on the laser sensor rather than the laser emitter. This has an important bearing on the design of any mounting frame as the centroid of the reference system will be off-centre from the scanner such that the scanner must be mounted asymmetrically (see Figure 3).

It is also important to note that the origin of any scans made will be the location (in terms of x, y and z co-ordinates) of the laser sensor at the very beginning of the scan. If the scanner is moved during a scan, the origin will remain at the initial location of the sensor.

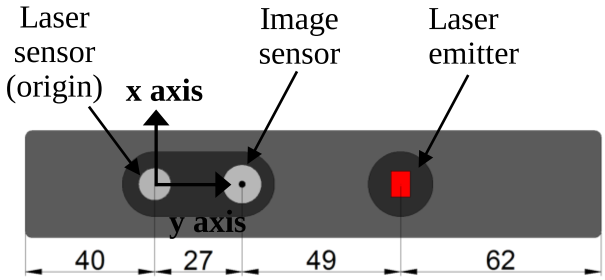

Figure 3. Diagram of the face of the scanner showing the location of the 3D scan output origin. Z axis is into the page (dimensions in mm).

Another key consideration is the height above the soil surface at which the scanner should be mounted. The optimal height for the scanner to operate at is 350 mm above the highest point of the soil surface; in this case the top of the spoil heaps. This is due to the fact that the scanner cannot observe objects closer than this, and additionally the resolution of the scans reduces as the distance from the scanner increases. The scanner has a field of view of 57.5° meaning that at a height of 350 mm the maximum scan width is 384 mm.

The application where the scanner was first to be used was in capturing the geometry of trenches created by model seabed ploughing (EPSRC Project: Seabed ploughing: modelling for infrastructure installation, EP/M000362/1 & EP/M000397/1). The required scan area was 2000 mm long by 350 mm wide, meaning that the scan required to be split into a number of sections to achieve a sufficiently high scan resolution.

A lightweight aluminium frame was constructed to mount the scanner in a secure manner onto linear bearings attached to the sides of the model container as shown in Figure 4. Whilst the scanner unit has a universal camera threaded mounting point, it was not possible to use this as it was found to be too flexible to restrain the scanner. In order for the sections of the scan to be recombined to create a single model, it is important that they are correctly aligned. This means that the scanner should be aligned to within 0.1° of the physical model to ensure that the individual scans intersect correctly at the interfaces where they meet.

The aluminium frame was connected to a 12V DC motor at one end of the model tank to allow it to be moved in a controlled manner, whilst a draw-wire transducer (DWT) accurately measured the displacement of the frame.

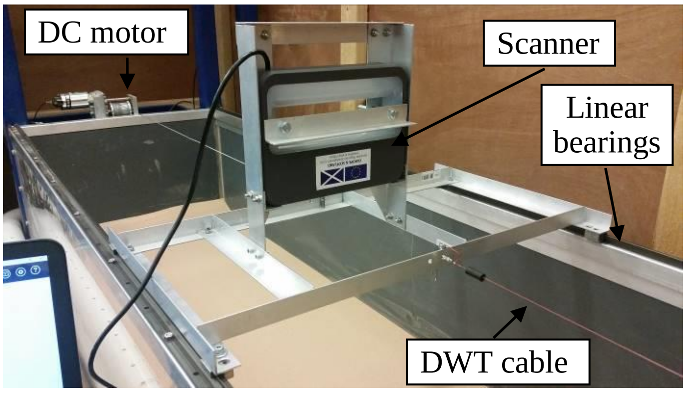

Figure 4. Mounting frame and linear bearings used to allow the scanner to be moved the full length of the model container.

3 SCANNING TECHNIQUE

The scanner unit itself is designed to be used hand held with the scanner tracking its own position in real time relative to parts of the object that have been already been scanned, and then calculating its new position. However, this is aimed at 3D objects that may be scanned by moving 360 degrees around them. This means that any errors in position tracking are corrected for as the scanner returns to its starting point. In the majority of cases in physical modelling a flat surface is being scanned and rotating fully around the model is not possible, meaning that position tracking errors are the main source of error in the scans. This is usually manifested in a curvature of the 3D scan. As a result, it is not advisable to scan long areas in one continuous scan.

To deal with this, the length of the sand bed was split into several sections to be scanned individually. The scanner and frame was positioned over the first section and the scan was then initiated. During the scan, the scanner was kept stationary whilst the surface geometry of the section was captured, and the scan was then ended. The scanner could then be moved to the next section and the process repeated. Depending on the material being scanned, some small (up to 5 mm in diameter) random patches of the surface may not be captured due to laser point reflection from the sand surface. If necessary, this can be solved by advancing the frame and scanner by a

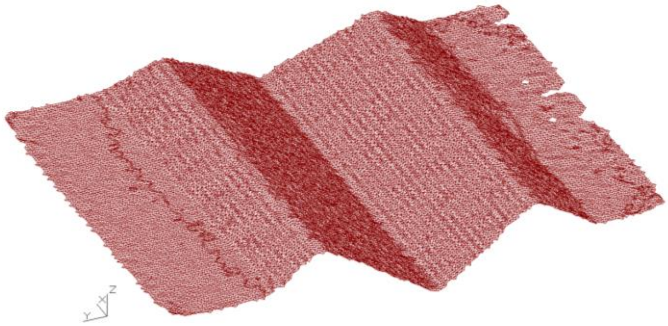

Figure 5. Typical individual section of 3D scan of trench.

small amount (2 mm) during the scan to allow the scanner to recognise the surface material.

This process was repeated every 200 mm (to ensure the scan sections overlapped) until the length of the plough trench was covered, scanning an area measuring 350 mm wide by 300 mm long each time (see Figure 5). The position of the mounting frame was recorded at each stage using the draw-wire transducer (DWT) so that the exact relative positions of each of the individual scans was known.

To scan the full 2000 mm length, 9 individual scan areas were required. The actual scan time required for the scanner to capture each area was only 5 to 10 seconds, and the full model could be scanned in 10 to 15 minutes. This included the time required for positioning the scanner over each of the 9 individual scan areas. Given that conventional hand measurements typically required 1 hour, this represents a significant time saving.

The Sense™ software automatically processed the point cloud at the end of each scan and created a dimensionally accurate 3D triangular mesh representation of the captured soil surface, aligned to the origin of the scanner (see Figure 5).

Each of these individual scans was saved as an object (OBJ) file, meaning that all of the dimensional units of the scan are preserved making it possible to measure features in the scan directly, without the need for scaling.

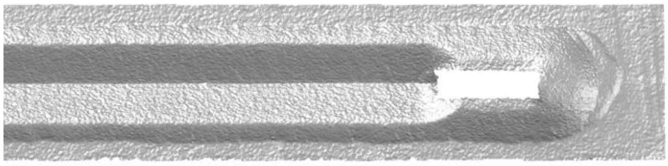

Figure 6. Plan view of typical recombined 3D scan of sand surface in AutoCAD post ploughing.

4 SCAN PROCESSING

To enable the scans to be recombined into a complete model, it was necessary to convert the OBJ file types into DWG format to allow editing in AutoCAD. This was done using Autodesk 3DS Max, where the scans were individually imported then exported as DWG files. The reason for the scans initially being saved as OBJ files is that these can be easily imported into 3DS Max, saving significant computation time. This conversion was a lossless process as the mesh structure of the model initially created by the scanner is preserved.

Once each of the scan sections was converted, it was opened in AutoCAD and combined with the others by positioning it using the relative positions of the scan origins recorded by the draw-wire transducer. Any required changes to the alignment or orientation of the scans to match any desired coordinate system could be easily applied at this point.

This allowed the complete model to be easily visualised and interrogated using conventional CAD commands and tools (see Figure 6). Examples include the ability to section the model to extract cross-sectional profiles of features of interest, measure features that would be easily disturbed by hand measurements and observe features which are not visible to the eye. AutoCAD can also be used to easily measure areas and volumes from the 3D scans. Additionally, the geometry of each physical model can be stored and used at a later date to examine and explain any unexpected behaviour which may have been missed by conventional hand

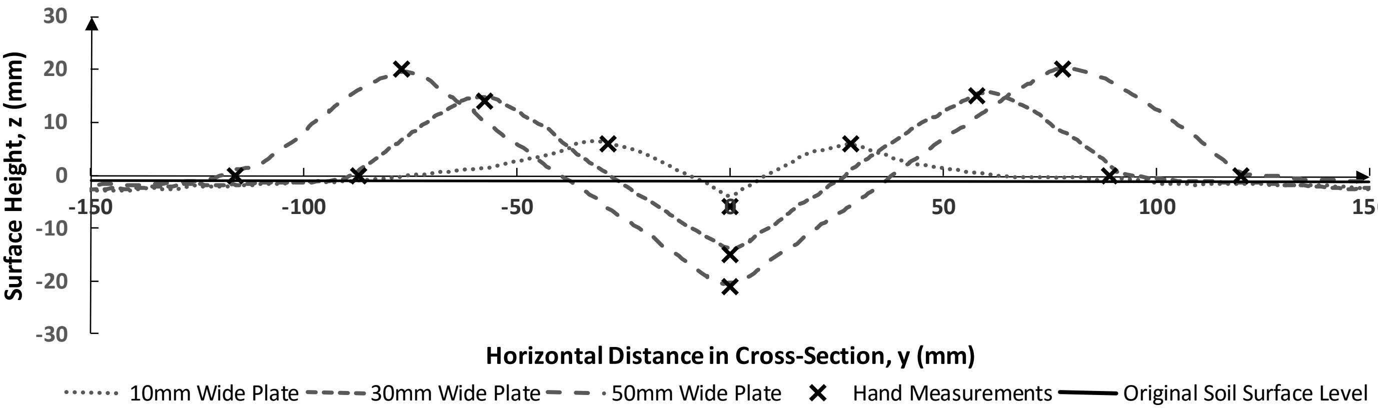

Figure 7. Cross-section trench profiles extracted from 3D scan data for three plough plate widths (at x = 1000 mm).

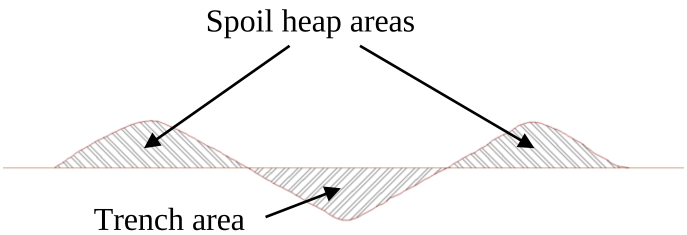

Figure 8. Estimation of the area of each part of the 3D scan surface cross-section using AutoCAD.

measurements.

In order for operations such as cross-sectioning to be carried out the scan must be converted from a mesh object to a surface object to allow editing. Once the required sections have been generated, they can be selected and exported to excel using the AutoCAD Data Extraction tool if required.

As previously mentioned, the scans were to be directly compared with the output from 3D numerical modelling software. This required the combined 3D scan to be in STL format in order to be compatible with the visualisation software. Normally, this would be done by exporting the STL file directly from AutoCAD, however, as the combined scan consists of several parts and does not form a continuous surface this was not possible. This can be overcome by importing the entire combined scan DWG file back into 3DS Max as a block and then re-exporting the block as an STL file.

5 RESULTS

To test the system, three different aluminium plates 150 mm high and 200 mm long with widths of 10, 30 and 50 mm were ploughed through a 150 mm deep bed of medium dense Congleton (HST95, Lauder et al, 2013) sand at a constant embedment depth of 80 mm (see Figure 1).

The surface profile of the trench and spoil heaps generated by each of the plates was recorded using the 3D scanning system. Hand measurements (in terms of x, y and z co-ordinates) were also taken at regular intervals along the sand bed of the location of the trench base, top of the spoil heaps and edge of the spoil heaps.

The cross sections of the trench profiles were then extracted from the 3D scans at a distance of 1 m (x = 1000 mm) from the starting position of the plates, where the plates had reached steady state (Lauder et al, 2012) and the trench geometries were no longer changing (see Figure 7). The hand-measurements have been overlaid onto the cross sections and, as can be seen, they coincided well with the trench cross-sections extracted from the 3D scans, indicating that the scanner is operating correctly.

The usefulness of 3D soil surface scanning was highlighted by the 10 mm wide plate in particular, where the edges of the spoil heaps were poorly de-

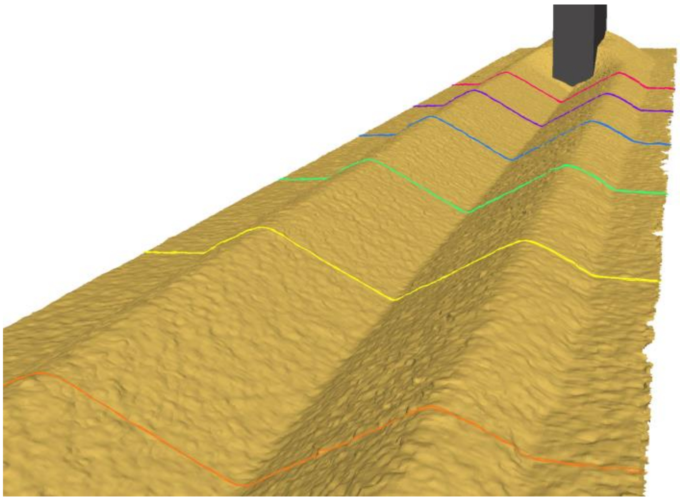

Figure 9. Example of use of ParaVIEW to annotate 3D scan directly.

fined. In this case, it was not possible to take hand measurements of the spoil heap edges as the edge was not visible to the eye, and only the 3D scanner was able to capture this data.

Another point to note was that the conventional method of measuring trenches using idealised straight line geometry can be improved upon using 3D scanning, which captures the true shape of the trench profile. This allows more accurate measurements of soil volumes to be made, allowing the net volume change during ploughing to be estimated for example.

By measuring the areas under the cross-section using AutoCAD (see Figure 8) the amount of dilation per unit length of trench for each of the plate widths tested was found, providing additional information useful for the analysis of plough performance (see Table 2).

Table 2. Areas for each section of the surface profile at x =1000 mm and net volume change of the cross section.

Plate width mm	Trench area mm^2	Spoil heap area mm^2	Volume change mm^2
10	-36.7	+345.8	+309.1
30	-462.2	+961.0	+498.8
50	-922.6	+1590.3	+667.7

6 COMPARISON WITH NUMERICAL ANALYSIS

Importantly, the 3D scanned surfaces can be used to validate the surface deformations predicted by numerical analysis of the physical models. One way this can be done is by comparing the key geometrical properties of the trench cross section such as the spoil heap height, trench depth and angle of repose (see Figure 8). The cross sections can either be created using AutoCAD as described previously, or alternatively by using numerical visualisation software such as ParaVIEW. ParaVIEW can be used to select locations of interest in the 3D scans (see Figure 9) and then easily extract images of the cross sections at these points. In operations such as this, ParaVIEW appears to be more efficient than AutoCAD in the post-processing of 3D surfaces.

In the current seabed ploughing project, predictions of 3D surface profiles from the numerical modelling will instead be directly compared with those from scanned laboratory experiments. Quantitative estimates of error in the former will be obtained by overlaying both data sets and automatically computing the differences in elevation and volume. This can easily be done using ParaVIEW.

7 CONCLUSIONS

A low cost 3D soil surface scanning system has been developed that allows the geometry of physical models to be captured to within an accuracy of ± 0.5 mm and the system provides 3D scan output in the form of an easily interrogated 3D model. Using conventional CAD software, the 3D model can be used to generate cross-sections of any areas of interest in the physical model. Tests on seabed ploughing trenches show that the scanner can capture the true form of the trenches more accurately than conventional hand measurements, allowing trench areas and spoil volumes to be better estimated. Direct comparison of the scans against output from numerical analysis is also possible allowing the verification of surface boundary predictions via computational modelling. In conclusion, 3D scanning presents an opportunity to improve the way that surface deformations are captured in geotechnical physical modelling research.

8 ACKNOWLEDGEMENTS

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