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ABSTRACT

Coded targets have been widely used for solving the corresponding problem in photogrammetry for high-accuracy three-dimensional measurements. Accurate and efficient recognition and identification of coded targets are of great importance in coded target-based photogrammetry. In this paper, an efficient and accurate method for coded target decoding was developed. In this method, blob analysis was performed to recognize the coded targets. Then, image processing, the RANSAC algorithm, and the interpolation technique were applied respectively to decode the coded targets, identify falsely identified coded targets, and recover missing coded targets. Interpolation was also performed on the membrane, which can significantly increase the density of the points on the membrane and produce more representative 3D results for the soils specimen. This method was implemented into a MATLAB program and all computation was done automatically by the computer program. This method takes advantage of the prior knowledge of the geometric arrangement of the coded targets. The effectiveness and accuracy of the proposed method are validated by implementing it into three-dimensional reconstruction of soil specimens during triaxial testing in geotechnical engineering. Experimental validation results indicate that the proposed method can achieve accurate and efficient coded target recognition and identification results.

INTRODUCTION

Over the past decade, increasing attention has been paid to using photogrammetry-based method to measure the deformations of soil specimens during triaxial test (Salazar et al, 2015, Zhang et al. 2015., Li et al. 2015., Fayek et al. 2020., Xia et al. 2021). Coded target (CT) has been widely used in photogrammetry-based method due to its low cost, sub-pixel high accuracy, and being easy to use (Knyaz and Sibiryakov, 1998., Fernandez-Fernandez et al. 2013). Figure 1 shows the triaxial cell and the CTs used in the triaxial test. In Figure 1, the CTs were readily printed on the sticker paper and attached to the surface of the acrylic cell, the frame rods, and the top and bottom pedestals. CTs were also printed on the rubber membranes for point measurement of the soil specimen. The enlargements of two randomly selected CTs were shown on the right side of Figure 1. The two CTs have different shapes and their associated IDs are 605 and 616, respectively. In fact, each CT in Figure 1 has a unique shape and unique associated ID.

In coded target-based photogrammetry, there are two essential and important steps:

CT recognition and CT identification (also referred to as CT decoding). CT recognition is to find the CTs and their locations in an image. CT identification is the process of determining the unique ID of each CT. The overall measuring performance and accuracy of the coded target-based photogrammetry are directly linked to the quality of the image point determination (Knyaz and Sibiryakov, 1998., Fernandez-Fernandez et al. 2013). Therefore, it is important to ensure accurate and efficient CT recognition and identification. However, due to poor image quality, unfavorable light conditions, inevitable scratches on the acrylic cell, etc., coded target-based 3-D measurements often suffer from unavoidably unsatisfactory target recognition and identification results. Manual correction, a tedious, time consuming, and prone to error process, is often required due to the low target recognition and identification accuracy (Xia et al, 2021). On the other hand, most current photogrammetry-based methods did not take advantage of the predesign information of the CT design.

This paper aims to develop an efficient and accurate method to automatically recognize and decode the CTs with applications to 3-D measurements of soil samples in triaxial tests. The proposed method uses blob analysis to recognize CTs. RANSAC algorithm is utilized to automatically identify wrong CT IDs. Interpolation technique is applied to find more CTs on both the acrylic cell and the membrane. The resulting CT identification information serves as input for 3-D reconstruction of the soil specimen.

PROPOSED METHOD

The overview of the procedure of the proposed method is shown in Figure 2. There are four phases in the proposed method. Phase 1 is to use a commercially available digital camera to take a group of about 30-40 images around the triaxial test equipment. Phase 2 is to perform CT recognition. Phase 3 is to conduct CT identification. Phase 4 is to use the CT recognition and identification results from Phases 1-3 to perform 3-D reconstruction of the soil specimen. In this paper, the detailed procedures of the proposed method are explained.

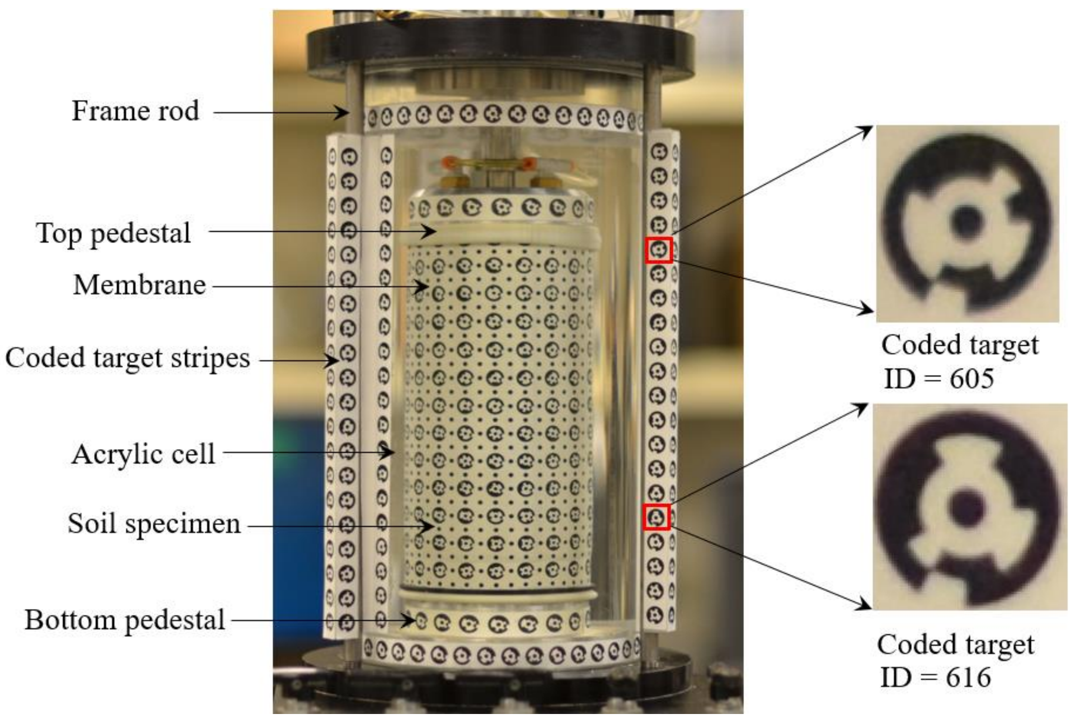

Figure 1. Triaxial cell and coded targets used in the triaxial test.

Image Acquisition

Good image quality is key to a successful photogrammetric project. Several factors influence the image quality, such as the image resolution, image capturing, shooting angles, the overlapping between images, and lighting condition, etc. In this study, a DSLR camera with an image resolution of 4928 by 3264 was used. It is found that the image resolution is good enough since most CTs on the images can be clearly seen. Images were taken around the triaxial cell at around 16 different positions. These 16 positions were roughly in a circle. At each position, two images were captured at two different shooting angles. The abovementioned image capturing method is to ensure sufficient overlapping between images and various shooting directions, which are beneficial to 3-D reconstruction. Each image was checked immediately after being captured to make sure every image is clear. Normal light in the room should be sufficient to produce good images. Even though it might seem to have many requirements regarding the image acquisition, these requirements are all easy to achieve and can significantly contribute to good CT recognition, CT identification, and 3-D reconstruction results.

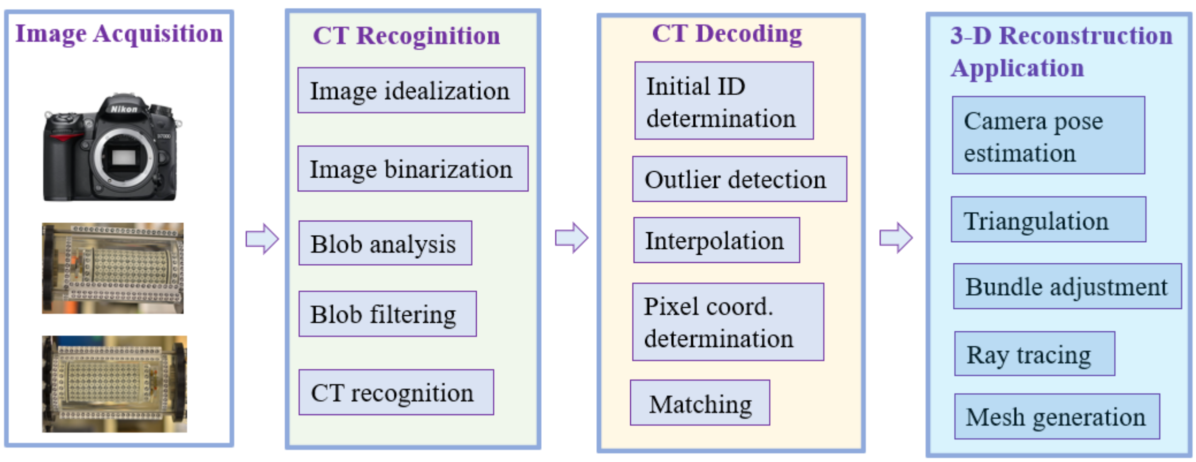

Figure 2. Overview of the procedure of the proposed method.

CT Recognition

It is important to correct the images for lens distortion (also referred to as image idealization) especially when the camera is wide angle camera and there is large images distortion. More discussion regarding image idealization can be found in Zhang et al, (2015) and Xia et al, (2021). After the image distortion was removed, image binarization was performed. Image binarization is an image processing technique that converts a grayscale image to black-and-white, which reduces the information contained within the image from 256 shades of gray to 2: black and white, a binary image. Image binarization is commonly performed in object extraction from an image. Figure 3a shows a triaxial cell image with CTs. Figure 3b is an enlargement of a portion of the rubber membrane and is used as an example to demonstrate and illustrate the proposed method. Figure 3c is the binary image of Figure 3b. Some other important steps in this phase are explained below:

Blob Analysis. A blob means connected pixels in an image. Blob analysis is to calculate statistics for labeled regions in a binary image. A lot of important information can be extracted from the image, such as the quantities of the area, centroid, bounding box, label matrix, blob count of the blobs, etc. Blob analysis is an efficient tool to extract the CTs from the image. In our case, the area of the blob is an important feature. So, the area of each blob was computed.

Blob Filtering. It is obvious that most CTs have similar areas as shown in Figure 3c. Therefore, it is easy to remove any blobs that have either very large areas or very small areas. This can significantly reduce the search range of CTs. It is found that the CT has a unique feature: in each CT, one small blob is embedded in a large blob. This can be clearly seen in Figure 3c. For each binary CT in Figure 3c, the small blob is inside a large blob. This distinctive feature sets the CTs apart from almost all other blobs. Figure 3d presents the CTs found by using this embedding feature. The boxes in Figure 3d represent the bounding box of the CTs. It is shown that this distinctive feature is the most important and useful feature of the CTs when performing CT recognition. It is found that most CTs can be successfully found and recognized by using the abovementioned blob filtering method based on area and the embedding feature.

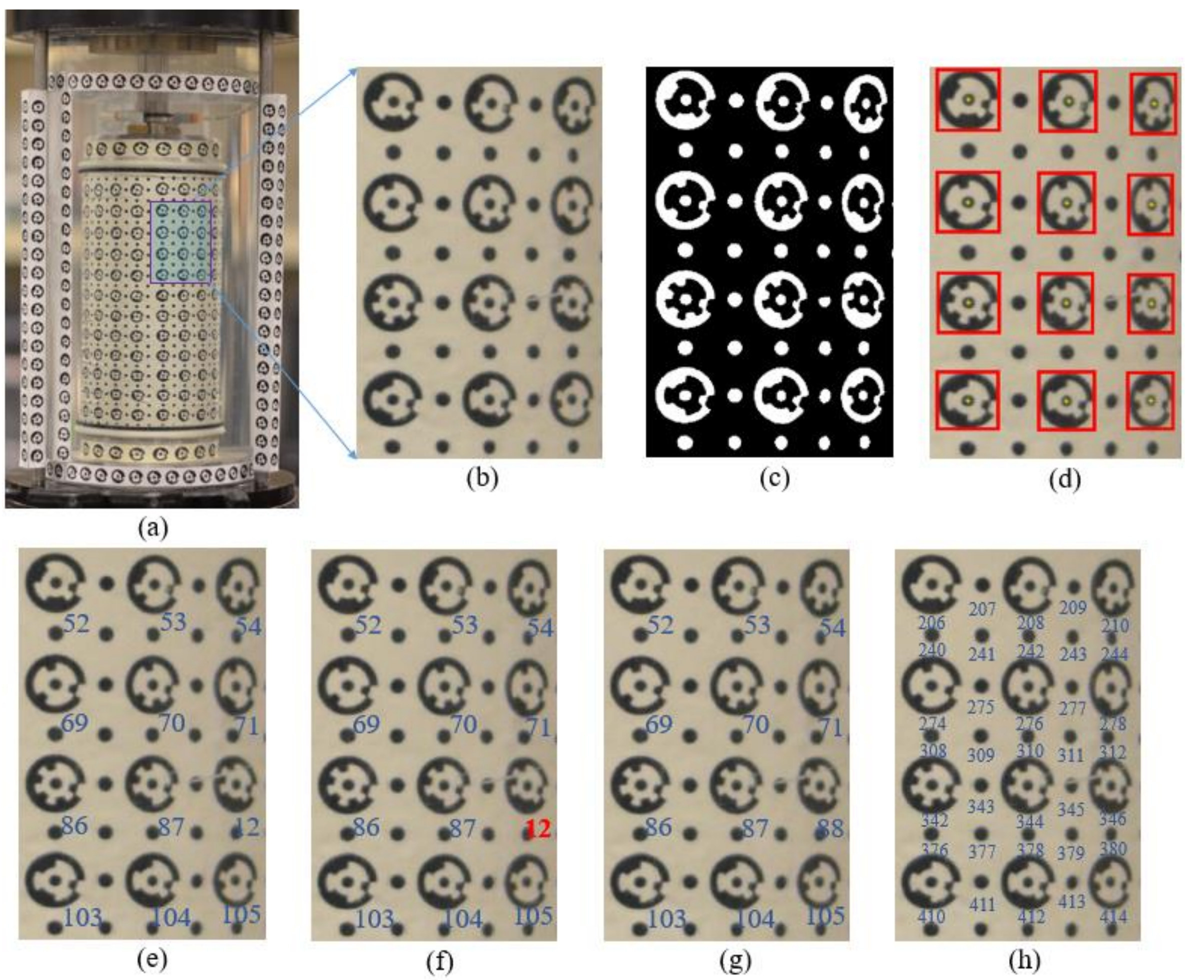

Figure 3. CT Recognition and decoding results. (a) the triaxial cell with CTs; (b) the enlargement of a portion of the rubber membrane; (c) binary image; (d) Recognized CTs by using the embedding feature; (e) initial CT IDs results; (f) Identification of outlier CT IDs; (g) ID results after correcting the wrong IDs; and (h) interpolating more points on the membrane.

CT Identification

In this phase, the ID of each recognized CT was obtained. We started with determination of the initial CT IDs. Then, the RANSAC algorithm was used to identify and correct the wrong CT IDs. Finally, the interpolation technique was utilized to recover more CTs and more solid dots on the membrane. More detailed regarding these steps are explained as follows:

Initial ID Determination. Each CT needs to be assigned a unique ID. The procedure for determining the initial CT IDs is briefly introduced here while a more detailed explanation can be found in Xia et al. (2021). The CT contour was identified by detecting the boundary of the CT. Then, ellipse fitting to the outer boundary of the CT was performed to obtain the orientation, major and minor axes of the CT. Then, the elliptical CT contour was normalized to circular contour by using equation. Finally, a signature-based CT contour representation technique was used to decode the CTs. In image processing, signature is a method for representing the contour of a bidimensional object by means of a one-dimensional function (Popescu, 2004). For each CT, the 12-bit binary numbers were obtained and converted to a decimal number, which corresponds to the ID number of the CT. Figure 3e shows the initial CT IDs results.

Outlier Detection. As mentioned previously, the wrong CT IDs (outliers) are unavoidable due to poor image quality, inevitable scratches on the acrylic cell, unfavorable light conditions, etc. Figure These wrong CT IDs will lead to inaccuracy or even failure in 3-D reconstruction. Manually correcting these wrong CT IDs is very tedious, time-consuming and prone to error since a lot of images are to be processed for a triaxial test. There is a clear need to develop an efficient and accurate method for identifying the outlier CT IDs. In this study, the RANSAC algorithm was utilized to identify wrong CT IDs. The flowchart of the RANSAC algorithm is shown in Figure 4. Assume the initial ID results for a group of CTs on the membrane are obtained. One can take advantage of the information regarding the geometric arrangement of the CTs. The CT IDs design information is summarized in Table 1. To identify the wrong CTs, two points were randomly selected from all the points that have IDs on the same column or row. The model parameters for fitting a line to the two points can be estimated. Then the distances of the points to the fitted line can be calculated. The number of inliers was counted. After a certain number of trials, the model parameters that produce the most inliers represent the correct model. In the meanwhile, the outlier CT IDs were identified. In Figure 3f, ID 12 is an outlier and can be identified by using the RANSAC algorithm. The wrong ID can be corrected by using the predesign information of the triaxial cell. The ID results after correcting the wrong ID are shown in Figure 3g.

Table 1. Coded Target ID Design

Stripe Name	Number of Stripes	Starting ID	Ending ID	No. of CTs/Per Stripe	Total No. of CTs
Membrane	1	1	255	255	255
Transverse circular stripes (inside)	2	401	457	17	34
Longitudinal stripes	3	501	760	20	60
Transverse circular stripes (outside)	2	801	940	40	80

Interpolation. There might still be some missing CTs. Interpolation was performed to recover some missing CTs and find more CTs. Theoretically, a minimum of two correct CTs which did not belong to the same row and the same column were sufficient to infer both the IDs and the estimated pixel coordinates of all the other neighboring CTs. This is because one can take advantage of the prior knowledge of the geometric arrangement of the CTs and the accurate preliminary ID and pixel coordinate results after outlier IDs rejection (Xia et al, 2021). Interpolation was also performed on the membrane to find more solid dots. In Figure 3h, the solid dots are also detected and decoded. This can significantly increase the number of points on the membrane and produce more representative 3-D results for the soil specimen.

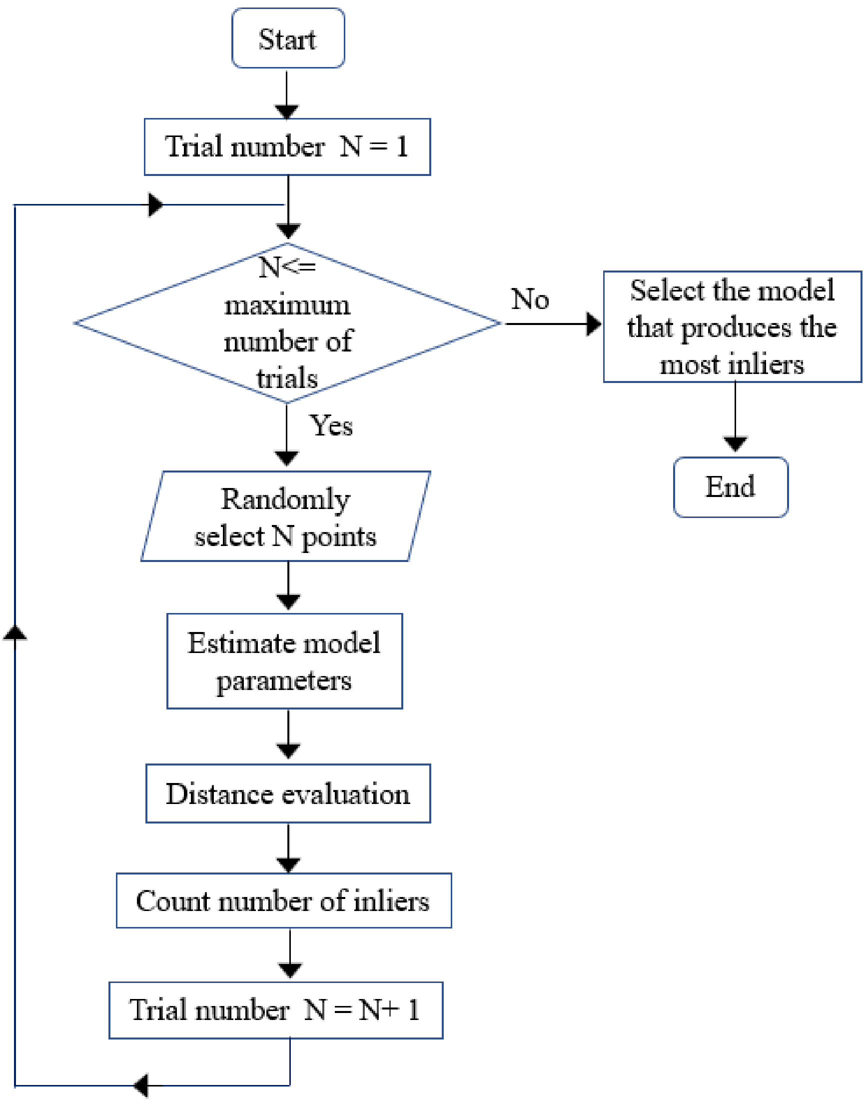

Figure 4. Flowchart for the RANSAC algorithm for detecting outlier CTs

3-D Reconstruction Application

After the CT IDs and pixel coordinates were obtained, a structure from motion photogrammetric method was used to obtain the 3-D model of the acrylic cell in the air. More details can be found in Xia et al. (2022). The soil specimen is immersed in water and obvious refraction is observed. So, the optical ray no longer travels through a single line and the refraction needs to be taken into consideration. In this study, a ray tracing technique proposed in Zhang et al (2015) was utilized to correct the refraction and obtain the correct 3D model of the soil specimen in water. After that, 3-D meshes were generated for the soil specimen. The generated 3-D meshes can be further used to determine the absolute volume of the soil specimen. For each loading step, the volume of the soil specimen can be obtained by using the method proposed by Fayek et al. (2020). By comparing the results for different loading steps, the volume-changes of the soil specimen can be obtained, and the localized strains can also be calculated. All the image processing procedures and calculation related to the 3-D reconstruction have been done by a MatLab program developed by the authors.

VALIDATION OF THE PROPOSED METHOD

Implementation of the Proposed Method into 3-D Reconstruction of Soil Specimen

In this section, the effectiveness of the proposed method was demonstrated by implementing it into the 3-D reconstruction of soil specimen during triaxial testing. A structure from motion photogrammetric method introduced in Xia et al. (2022) was adopted to obtain the 3-D model of the acrylic cell in the air. Then, the ray tracing technique introduced in Zhang et al, (2015) was utilized to obtain the 3-D model of the soil specimen under refraction condition. A total of around 35 triaxial test images were used for the validation test. The CT recognition and identification results obtained by the proposed method served as the input to 3-D reconstruction of the soil specimen. Figure 5 shows the 3-D models of the acrylic cell and soil specimen. The 3-D models of the acrylic cell and the soil specimen in Figure 5 indicate that the proposed method is effective and accurate in terms of CT recognition and identification.

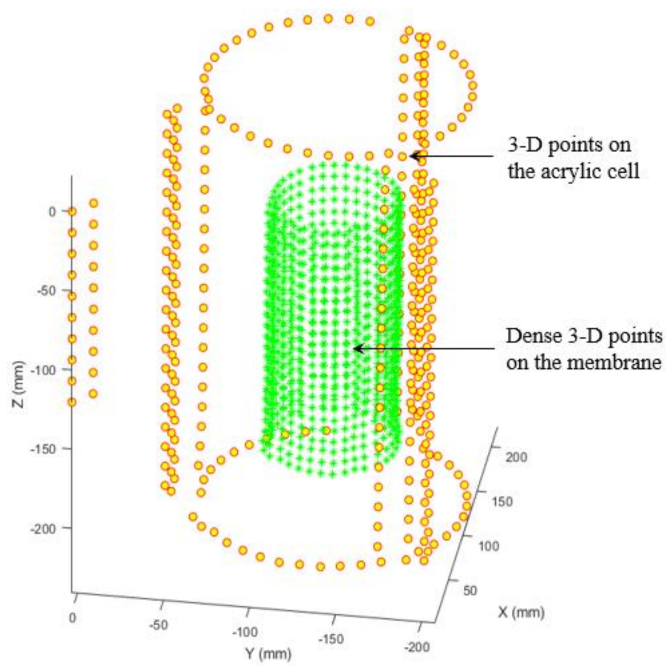

Figure 5. 3-D model of the soil specimen.

CONCLUSION

This paper presents an efficient and accurate method for coded target decoding with application to 3-D reconstruction of soil specimen. Blob analysis was performed to recognize the CTs and the RANSAC algorithm was utilized to automatically detect the outlier CT IDs. The CT IDs and pixel coordinates obtained by the proposed method can be further used to perform 3-D reconstruction of the acrylic cell and determine the 3-D points on the soil specimen. The proposed method has been implemented into a MATLAB program. Therefore, all the computation can be automatically done by the computer program within a few minutes. The proposed method enables automatic identification of outlier CT numbers, which is a huge advantage since the tedious and prone-to-error manual corrections of false CT identifications can be eliminated. Another advantage of the proposed table method is that it takes advantage of prior knowledge of the CT arrangement. The geometric arrangement of nearly all CTs is carefully designed before posting on the surfaces of measuring objects for the 3-D measurement purposes. Therefore, the proposed method has a wide application in most coded target-based photogrammetry tasks.

REFERENCES

Fayek, S., Xia, X., Li, L., and Zhang, X. (2020). Photogrammetry-Based Method to Determine the Absolute Volume of Soil Specimen during Triaxial Testing. *Transportation Research Record*, 2674(8), 206-218.

Fernandez-Fernandez, M., Alonso-Montes, C., Bertelsen, A., and Mendikute, A. (2013). “Industrial Non-intrusive Coded-Target Identification and Decoding Application.” In *Iberian Conference on Pattern Recognition and Image Analysis*. Springer, Berlin, Heidelberg. pp. 790-797.

Li, L., Zhang, X., Chen, G., and Lytton, R. (2015). Measuring unsaturated soil deformations during triaxial testing using a photogrammetry-based method. *Canadian Geotechnical Journal*, 53(3), 472-489.

Knyaz, V. A., and Sibiryakov, A. V. (1998). Non-contact 3D model reconstruction using coded targets. *Image* 1(2).

Popescu, C. (2004). *A Contour Based Descriptor for Object Recognition. SACI Transactions, Timisoara*.

Xia, X., Zhang, X., and Yin, Z. (2020). “A Photogrammetric Computer Vision Approach for 3D Reconstruction and Volume-Change Measurement of Unsaturated Soils.” In *Geo-Congress 2020: Geo-Systems, Sustainability, Geoenvironmental Engineering, and Unsaturated Soil Mechanics 2020 Feb 21* (pp. 387-393). Reston, VA: American Society of Civil Engineers.

Xia, X., Zhang, X., Fayek, S., and Yin, Z. (2021). A table method for coded target decoding with application to 3-D reconstruction of soil specimens during triaxial testing. *Acta Geotechnica*, 16(12), 3779-3791.

Xia, X., Zhang, X., and Fayek, S. (2022). *A Structure from Motion Photogrammetric Method to Measure the Volume-Changes of Unsaturated Soils during Triaxial Testing*. In preparation.

Zhang, X., Li, L., Chen, G., and Lytton, R. (2015). “A photogrammetry-based method to measure total and local volume changes of unsaturated soils during triaxial testing.” *Acta Geotechnica*, 10(1), pp.55-82.

Fayek, S., Xia, X., Li, L., and Zhang, X. (2020). Photogrammetry-based method to determine the absolute volume of soil specimen during triaxial testing. *Transportation Research Record*, 2674(8), 206-218.