

A 3D imaging method for in-situ non-destructive roots monitoring

R. Brigante¹, L. Marconi¹, A. Lepri¹, A. Fraccica², M. Cecconi¹

¹*CIRIAF - Department of Engineering, University of Perugia, Perugia, Italy*

²*Department for the Geological Survey of Italy, ISPRA, Rome, Italy*

ABSTRACT: Root architecture is commonly represented by the root area ratio, to be experimentally acquired at different depths from the ground table, generally from direct observations. However, roots imaging systems are rapidly developing in several scientific fields linked to the study of the soil-vegetation interaction. In the context of an extensive experimental study aimed at evaluating the role of vegetation in a debris flow's source area, the paper presents an experimental method for non-destructive, in-situ monitoring of roots properties and architecture. The results of a preliminary simplified laboratory setup are firstly presented and discussed. Structure-from-Motion (SfM) techniques are then applied to reconstruct a dense 3D point cloud of the observed scene. After filtering the point cloud based on colour and shape to isolate separate roots, morphological features such as length and thickness are extracted and quantified. Repeating the acquisition over time enables continuous monitoring of roots development, spatial evolution and growth dynamics.

Keywords: Non-destructive roots architecture survey; Structure from Motion (SfM); 3D point cloud

1 INTRODUCTION

In the context of a broad laboratory and experimental research currently in progress, investigating the role of vegetation in controlling the hydro-mechanical behaviour of steep slopes surrounding a thick debris-flow deposit in the Mounts Sibillini National Park (Norcia, PG, Central Italy), this paper presents the preliminary results of a photogrammetry-based methodology proposed for detecting the in situ roots architecture developing in the shallow top soil. The hydro-mechanical properties of the rooted soils in the investigated area are presented in a companion paper (see also Lepri et al., 2025; Fraccica et al., 2025a, Fraccica et al., 2025b).

The detection of 3D root architecture has been widely studied in recent years (Rahman et al., 2020). Any differences in the spatial distribution of the root system within the soil may greatly affect the efficiency with which the soil-root system carries out physiological functions such as water and nutrient acquisition.

Geophysical imaging techniques such as radar or seismic tomography can be used to identify roots and the root zone. Despite their high resolution, radar techniques penetrate poorly into the moist root zone and do not allow soft roots to be distinguished from woody ones (Attia al Hagrey, 2007). Therefore, complementary techniques as the one proposed in this article are important to derive quantitative morphological root indexes and derive information about root growth. For this reason, the use of multiple exploration tubes close to the studied vegetation individual is recommended.

In the last years, X-ray CT scanning, with high-resolution characteristics, has allowed to assess root architecture geometry and its effect on soil porosity and grain kinematics within geotechnical laboratory specimens (Fraccica et al., 2025c; Anselmucci et al., 2021; Carminati et al., 2013). The adoption of these laboratory techniques leads to a very quantitatively accurate evaluation of the root system; however, despite of the lower accuracy in the measurements, the recurrence to much simpler devices could be useful to detect the current in situ roots-architecture in the field. This has motivated the design and manufacturing of a very simple in situ equipment to provide, with sufficient accuracy, the actual in situ configuration of the roots inside the soil.

The equipment, currently in its early stages, consists of a fixed transparent cylindrical tube to be installed at a given depth into the rooted soil, after pre-drilling with casing. The prototype allocates a motorized mechanism which rotates a video-camera inside the tube, enabling automated image acquisition of the rooted soil from fixed positions and multiple viewpoints (see Figure 1). To this aim, the cylinder's thickness and the optical properties of the tube-material are both key factors. In the paper, only the preliminary laboratory set-up is described, with the aim of validating the survey method, the data acquisition procedure to isolate roots and detect the roots architecture, as well as the results interpretation.

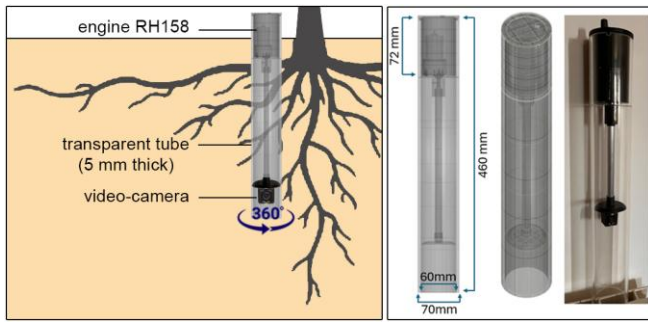


Figure 1. Schematic view of the in situ-equipment (prototype)



Figure 2. Trench for roots quantification in the field

2 LABORATORY SETUP AND SURVEYING TECHNIQUES

In this section, the morphology of the roots is first described. Then, a photogrammetry-based method is proposed for estimating the root architecture. The area under investigation is mainly covered by a beech forest (Fraccica et al., 2025b). The beech tree's finer roots are generally developing down to 1 m below the ground surface in the topsoil (Bischetti et al., 2009).

2.1 Roots type

Beech tree's roots were retrieved, in the field, from trenches with cross section of 0.15 m x 0.15 m and depth of 0.5 m (Figure 2). The root diameter classes with the higher associated total lengths (*i.e.* the most frequent root's diameters) are between 1.0 and 1.5 mm (Fraccica et al., 2025b). Considering that the average soil grain size D_{50} is 4 mm and the average soil pore size is $x_{50} = 0.30 \times D_{50} = 1.20$ mm, according to Kamiya and Uno (2000), roots' diameters are comparable to soil pore sizes and potentially induce soil grain displacements during their growth, with consequences on the hydro-mechanical behaviour of the vegetated matrix. Some rare thicker roots between 2.5 and 4.5 mm were also found.

2.2 Simplified laboratory setup

In this preliminary stage, a laboratory setup (Figure 3, left) was designed to reproduce, in a simplified way, the conditions of the in-situ measurements. A transparent

glass cylinder (dia.: 140mm) was placed within a cardboard container, which served to reduce ambient light, even if still far from those in field conditions. Small checkerboard targets (10 mm in size) and a metric scale of known length (50 mm) were attached to the inner surface of the cylinder to improve the image alignment and to scale the model to real-world dimensions during subsequent processing. A sample of six roots of varying shapes and sizes, retrieved from the test site were positioned on a polystyrene base very close to the external cylinder surface. An iPhone 15 Pro Max was placed inside the cylinder for image acquisition.

3 SURVEYING TECHNIQUES AND RESULTS

The root system was investigated using a photogrammetric approach, acquiring overlapping images to ensure complete coverage. This enables three-dimensional modelling at a resolution consistent with image quality, capturing fine root traits.

The reconstruction was performed using the Structure-from-Motion (SfM) algorithm, which estimates camera positions from overlapping images and generates a dense point cloud, providing a detailed 3D model of roots and their surrounding environment. Although photogrammetry is widely used across scientific fields, few studies have applied it to non-destructive in situ root analysis (Arief et al., 2024; Okamoto et al., 2022).

To assess technique accuracy, roots were also placed on a base with targets of known coordinates and photographed with a Sony Alpha 58 camera, enabling scaling to real size and geometric measurements in a CAD environment (Figure 3, right).

3.1 Data Acquisition

Data acquisition was performed by recording a video from inside the cylinder, while rotating the iPhone 360° with a support rod, and shifting the rotation centre vertically between two different positions (Figure 3, left). After enhancing image sharpness, 500 frames were extracted, ensuring an overlap of approximately 90% between consecutive images. This procedure was preferred over taking individual photographs, to ensure consistent overlap and avoid coverage gaps.



Figure 3. Experimental laboratory setup (left), and image acquired by Sony camera (right)

3.2 Points cloud and roots features

The extracted frames were processed in Agisoft Metashape (v. 1.7.4) following a standard SfM workflow: importing images and automatically identifying homologous points, including features and artificial targets on the inner cylinder surface; generating a sparse point cloud; evaluating possible alignment errors; applying the metric scale for real-world dimensions; and producing a dense point cloud. As a result, the camera positions during acquisition and the sparse point cloud were obtained along with a detailed 3D reconstruction of the roots and their surrounding environment (Figure 4, left). The reconstruction accuracy, assessed using the metric scale, was within sub-millimetric mean error. The transparent cylinder was not reconstructed, and the small targets on its inner surface slightly occluded minor portions of the roots, without significantly affecting visibility.

Individual roots were isolated from the overall point cloud in Cyclone 3DR (v.2024.0.1; Figure 4, right) and filtered by colour to remove background points, mainly from the cardboard container. The isolated roots were then analysed to assess their morphological properties (Figure 5, left), with features evaluated at 20 mm intervals. Each root was divided into segments homogeneous in diameter and inclination. Each segment was then used to generate an equivalent cylinder, and the axes of the cylinders were combined to define a polyline representing total root length (Figure 5, centre). Cross-sectional planes orthogonal to the root axis were positioned every 20 mm, to measure local diameters (Figure 5, right). This procedure enabled a detailed quantification of root morphology, capturing both longitudinal and radial variations with high spatial resolution. The same features were then measured in a CAD environment on the image previously acquired with the Sony camera (Figure 6).

The comparison between radius extracted from the 3D point cloud and CAD measurements along different depths shows a generally good agreement ($R^2 = 0.75$, see Figure 7, top), while root lengths exhibited even closer agreement ($R^2 = 0.99$, see Figure 7, bottom). Differences between point cloud and CAD based-measurements, were quantified using the mean, the standard deviation, and the mean of absolute values, yielding values of 0.06, 0.26, and 0.20 for radius, and 1.00, 2.43, and 2.10 for length, respectively. These results demonstrate that the photogrammetric approach provides reliable and reproducible measurements of both root diameters and lengths, with higher accuracy observed for the latter.

4 FURTHER PERSPECTIVES

The preliminary test presented in this paper demonstrates the potential of a non-destructive technique that preserves the integrity of the roots while enabling repeated analysis on the same root systems. Working di-

rectly on the 3D point cloud ensures objective and reproducible measurements of geometric roots features such as diameter and length. Moreover, the digital model can be archived and re-analysed (in case), allowing measurements to be repeated or extended as new processing methods become available.

For future in-situ applications by developing the prototype, several aspects require further evaluation. The geometry (both diameter and length) of the transparent tube will influence the field of view, the observable depth, and the feasibility of installation. The choice of the camera is equally important, as sensor resolution, focusing capability, and optical quality determine the level of detail in the reconstruction.

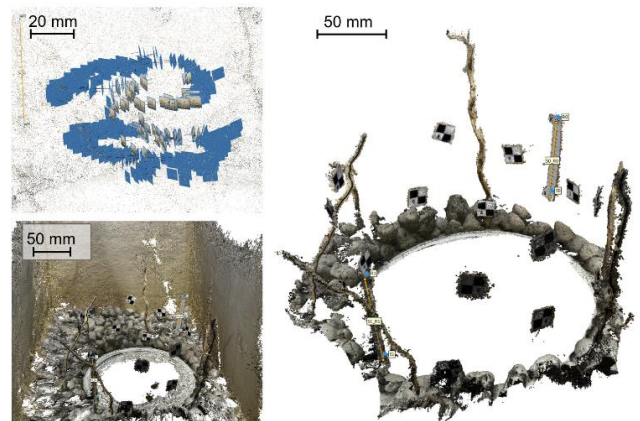


Figure 4. Camera positions (top left); dense point cloud (bottom left); isolated roots (right)

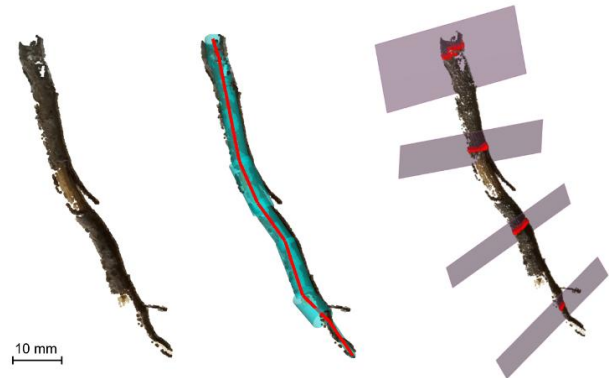


Figure 5. Point cloud of isolated root (left), equivalent cylinders (centre) and cross-sectional planes (right)

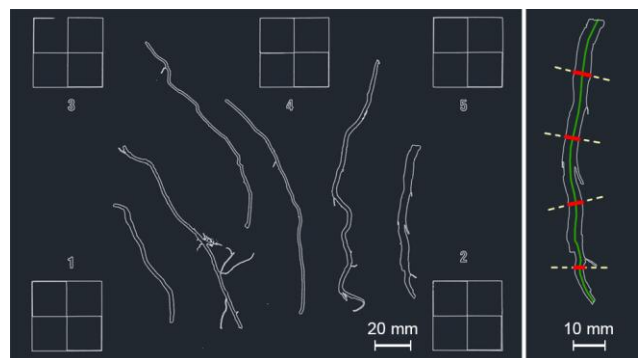


Figure 6. Geometric features extracted in CAD environment

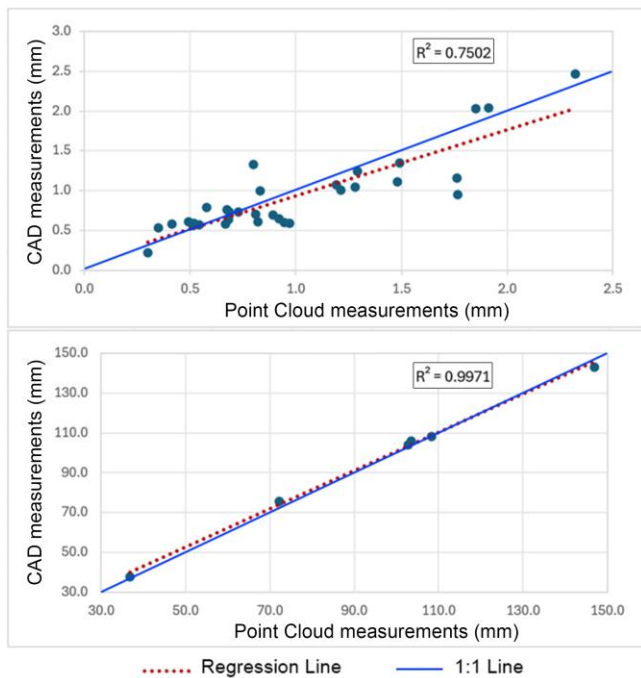


Figure 7. Scatter plots comparing radius (top) and length (bottom) measurements from point cloud and CAD model

Soil physical properties may also affect the quality of results gained by this approach: heterogeneous colours or tones of the soil environment could be similar to those of roots and thus may hinder segmentation and filtering. Controlled and homogeneous illumination will likely be required to ensure consistent image quality. Other factors, such as the tube features (material, thickness, optical effects) the durability of calibration targets, and the possible integration of automated acquisition systems, should also be considered to guarantee repeatability over time. It should also be noted that the experimental technique, based on the photogrammetric approach, reconstructs only objects visible to the camera, *i.e.*, those in direct contact with or clearly exposed along the cylinder surface. In order to reduce the disturb in isolating roots from the surrounding soil, prior to their analysis, this methodology can be combined with trenches (see Figure 2) to determine and correlate root contents or to monitor root development over time using images taken at various time steps, without continuously disturbing the vegetation. Once the tubes are installed in the field, a combined use of optical and infrared sensors could be also envisaged to evaluate the soil water contents and the roots' physiological state. Therefore, beyond these methodological aspects certainly require further and detailed investigation, the presented approach appears to be promising and shows some potential for its in situ applications.

5 ACKNOWLEDGEMENTS

This study has been funded through a project under the Italian National Recovery and Resilience Plan (NRRP).

6 REFERENCES

- Anselmucci, F., Andò, E., Viggiani, G., Lenoir, N., Arson, C., Sibille, L. 2021. Imaging local soil kinematics during the first days of maize root growth in sand, *Scientific reports* **11**(1), 22262.
- Arief, M.A.A., Nugroho, A.P., Putro, A.W., Sutiarto, L., Cho, B.K., Okayasu, T. 2024. Development and Application of a Low-Cost 3-Dimensional (3D) Reconstruction System Based on the Structure from Motion (SfM) Approach for Plant Phenotyping, *J. Biosyst. Eng.* **49**, 326–336.
- Attia al Hagrey, S. 2007. Geophysical imaging of root-zone, trunk, and moisture heterogeneity, *Journal of experimental botany* **58**(4), 839-854.
- Bischetti, G.B., Chiaradia, E.A., Epis, T., Morlotti, E. 2009. Root cohesion of forest species in the Italian Alps, *Plant and soil* **324**(1), 71-89.
- Carminati, A., Vetterlein, D., Koebernick, N., Blaser, S., Weller, U., Vogel, H. J. 2013. Do roots mind the gap? *Plant and Soil* **367**(1), 651-661.
- Fraccica, A., Lepri, A., Papini, N., Cecconi, M. 2025a. On the measurement of in situ unsaturated shear strength of a beech-rooted soils. *E3S Web Conf., 5th European Conference on Unsaturated Soils and Biotechnology applied to Geotechnical Engineering* **642**.
- Fraccica, A., Cecconi, M., Lepri, A., Tagarelli V. 2025b. On the measurement of laboratory and field retention states of a loose coarse and vegetated topsoil. (Submitted for the *21st International Conference on Soil Mechanics and Geotechnical Engineering, Vienna 2026*).
- Fraccica, A., Romero, E., Fourcaud, T. 2025c. Effects of vegetation growth on soil microstructure and hydro-mechanical behaviour, *Géotechnique* **75**(3), 293-307.
- Kamiya K., Uno, T. 2000. Grain size and void diameter distributions of sands. In: *Unsaturated soils for Asia. Proceedings of the Asian Conference on Unsaturated Soils, UNSAT-ASIA 2000*, 399-404. Balkema, Singapore.
- Lepri, A., Fraccica, A., Tagarelli, V., Vaunat, J., Cecconi, M. 2025. Some remarks on the possible effects of vegetation cutting on the triggering of debris flows in Central Italy. *Proc. of the 9th Int. Symposium for Geotechnical Safety and Risk (ISGSR 2025)*. Oslo, in print.
- Liu, L., Fang, H., Wei, X., Liu, Y., Gao, W., Li, B., Zhou, H. 2024. Research advances on using X-ray CT in the study of 3-D root architecture, *Journal of Plant Nutrition and Fertilizers* **30**(2). 375-384.
- Lu, Y., Wang, Y., Chen, Z., Khan, A., Salvaggio, C., Lu, G. 2021. 3D plant root system reconstruction based on fusion of deep structure-from-motion and IMU, *Multimed Tools Appl* **80**, 17315–17331.
- Okamoto, Y., Ikeno, H., Hirano, Y., Tanikawa, T., Yamase, K., Todo, C., Danoura, M., Ohashi, M. 2022. 3D reconstruction using Structure-from-Motion: a new technique for morphological measurement of tree root systems, *Plant Soil* **477**, 829–841.
- Rahman, G., Sohag, H., Chowdhury, R., Wahid, K.A., Dinh, A., Arcand, M., Vail, S. 2020. SoilCam: a fully automated minirhizotron using multispectral imaging for root activity monitoring, *Sensors* **20**(3), 787.