Received: 17 June 2021 | Revised: 25 January 2022 | Accepted: 30 January 2022

DOI: 10.1002/cae.22499

RESEARCH ARTICLE

WILEY

Open-source terrestrial laser scanner for the virtualization of geometrical entities in AEC classrooms

Carlos Ramonell | **Rolando Chacón**

Department of Civil and Environmental Engineering, School of Civil Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain

Correspondence
Rolando Chacón, Department of Civil and Environmental Engineering, School of Civil Engineering, Universitat Politècnica de Catalunya, C/Jordi Girona 1-3. Campus Nord UPC. Building C1. Barcelona 08034, Spain.
Email: rolando.chacon@upc.edu

Funding information
European Commission, Grant/Award Number: 958161; Institut de Ciencies de la Educació. UPC

Abstract

This paper depicts a case study that shows an open-source Terrestrial Laser Scanner (TLS) for use on the virtualization of simple yet precise geometrical entities in AEC classrooms. For bringing this technology to AEC classrooms, an open-source TLS was developed. The physical model was built using digital fabrication, its connectivity was established using accessible, affordable, open-source sensors and actuators and its digital representation was developed using generative design tools. All elements together are synchronized in real-time and the TLS becomes live, digitally twinned, geometry generator. The points that are generated by the TLS are gathered in a 3D virtual space in the form of virtual points. The present digitally twinned vision of laser scanning has thus three identified educational uses: (i) illustration of the measuring principle using open-source hardware together with mathematics and statistics, (ii) illustration of the generation and visualization of point clouds in real-time within a CAD environment, and (iii) perhaps with a vaster scope in AEC classrooms, illustration of the usage, analysis and identification of these point clouds. The development of this tool belongs to a vaster project for infusing Construction 4.0 technologies in AEC classrooms under development at the School of Civil Engineering of UPC-BarcelonaTech. The illustration to students of all these concepts with accessible technological tools is expected to enlarge their vision of more advanced constructional technologies such as cyber-physical systems for monitoring and surveying as well as digital technologies for reproducing "As-Built" models.

KEYWORDS

BIM, Construction 4.0, Digital Twins, Grasshopper, Terrestrial Laser Scanner

Correction added on 21 February 2022, after first online publication: The name of the School of Civil Engineering of UPC-BarcelonaTech is added in the abstract and the conclusion.

1 | INTRODUCTION

Emerging technologies in Architecture, Engineering, and Construction are transforming and creating new opportunities in the sector [37]. Technological advancements are permeating all layers of the sector and thus, it is required to adapt all layers of information within AEC curricula for educating and up-skilling AEC students, workers, and professionals [22]. There is a global trend for higher digitalization in the construction sector. To adopt technology, the industry needs to understand and contextualize the risks and benefits of using these emerging trends. Education is a fundamental part of this adoption [2]. Fabrication has become digital; digitalization of assets has become ubiquitous and digitalization of the behavior of the assets is becoming relentlessly twinned with virtual replicas. This physical-to-digital-to-physical data flow is creating new paradigms for the design and construction of built environment assets.

Building Information Modelling (BIM) changed paradigms one decade ago. The level of implementation of BIM in the market is presently high enough. Education-wise, BIM has hitherto been adopted by many AEC-related schools and universities [1,42,46,52,54]. BIM-friendly environments are crucial for interoperability and as result, they represent an ideal standard in education at various levels. All sorts of three-dimensional (3D) branches such as modeling, measurement, simulation, monitoring, construction tracking, and computational geometry can seamlessly communicate one to another. Proper ontologies and protocols are being established for such purposes.

The generation of as-built BIM models or monitoring assets using surveying requires measuring the geometry and appearance of an existing facility. Subsequently, those measurements need to be infused within high-level, semantically rich representations with standards industry agrees upon. Years ago, detailed measurement of an entire facility required a considerable amount of time and labor force with up-to-date equipment. Nowadays, both terrestrial laser scanning (TLS) and computer vision-based techniques are increasingly employed in construction sites for such purposes [20,4].

On the other hand, an aspect that is nowadays gaining momentum in the educational sector is the use of constructivist environments for fabrication, creation, and hands-on activities in the engineering classrooms. When designing experiments or when designing auxiliary tools for the developments of such experiments, fabrication technologies such as 3D printers, open-source Hardware, and open-source Software and programming become powerful, affordable, and accessible tools. As a result, the fabrication and "making" of the interfaces becomes a holistic project that may be entirely performed by students in labs infused with affordable tools and platforms [31].

This paper presents a proof of concept of an educational cyber-physical emerging technology for AEC-related classrooms. A TLS entirely made from scratch, that allow students to navigate from digital-to-physical-to-digital realms is presented. The geometry of the TLS is first designed digitally, it is subsequently materialized physically and thus, it is digitally twinned in real-time. The TLS is built using 3D printing, open-source Hardware, and open-source Software. Once the TLS is operable, its natural digital location is a generative design tool in which many other educational applications can be created using computational geometry. These applications can be fully embedded within BIM-enabled platforms. As a result, the TLS represents a digital twin, which is itself a digital twin generator for civil engineering classrooms. As geometries, simple yet precise geometrical entities are systematically presented to students for proper identification. Furthermore, it is worth pointing out that a real-time visualization of the measurements can be deployed, which provides synchronous feedback from/between students during lectures.

The paper is organized in three parts. First, a brief review of the literature in Section 2, a brief description of technical parts of the tool in Sections 3–4. Finally, a description of a set of AEC-related educational applications together with a discussion of the results in Sections 5 to 9.

2 | LITERATURE REVIEW

2.1 | Applications of TLS in AEC

Research in advanced applications using TLS is nowadays abundant. TLS-based techniques allow registering accurately and efficiently enormous 3D geometrical information in the form of point clouds, which have impacted in the manner surveying and management is conducted in AEC industries [17].

Point cloud data treatment and processing has been a major challenge since the dawn of the massive development of TLS applications. Consequently, point cloud feature extraction, semantic segmentation, and object recognition procedures represent active research trends [12,47]. Point cloud information management has generated a wide range of applications in multiple fields within AEC. For instance, in road and railway transportation networks, TLS have been used for road surface monitoring and off-road feature detection such as side markings, detection of pavement cracks, identification of traffic signs, or quantification of side vegetation [53,41]. Earthwork volume calculation has also been a common application [40] as well as the assessment of drivers' sight distance [15] and inspection of railways geometric irregularities [26]. In Forestry, analyses over time of changes in forest parameters as well as vegetation inventories have been performed [13,30]. In tunnel engineering, for the past 15 years, laser scanners have been used for monitoring the geometry of tunnels during excavation, performing deformation measurements, and extracting geological features [48]. Also, laser scanners are producing 3D representations of large urban areas being able to extract most attributes within them [45].

In buildings, research shows TLS technologies used in construction fields to undertake specific, unsafe, labor-intensive, and time-consuming tasks which require qualified personnel. Examples regarding dimensional quality assessments (DQA) include studies conducted on formworks and rebars [19] or geometric quality inspections (GQI) on prefabricated construction elements [23]. Moreover, quantification of initial imperfections of steel frames for further use in structural analysis have been performed within laboratory facilities [9].

Notwithstanding, a research trend regarding applications of 3D scanning technologies in construction is currently placed on migrating the scanned 3D information to a BIM-based environment. These processes are focused on either generating "as-built" or "as-is" 3D BIM models (Scan-to-BIM) or aligning an existing "as designed" BIM model with the scanned data, allowing peer-to-peer unique object identification and comparison of, for instance, MEP works [3] (Scan-vs-BIM). Research in Scan-to-BIM methodologies encompasses identification and updating of structural elements and materials [55,49,51], model generation of as-built indoor structures [18] or inventorying historical heritage structures with complex geometries [36,39]. Research on Scan-vs-BIM algorithms show how an update of position and shape of elements within a model can be established [33]. The status of particular activities during construction can be determined by providing the percentage of completion (POC) of a given project [32]. Similarly, quality control and assembly on prefabricated modular construction projects can be improved by integrating BIM and 3D laser scanning technologies [24].

Furthermore, research dedicated to enable raw "as-built" 3D point cloud data to generate improved numerical models has been published, where the major task is to transform point cloud data into simplified and accurate geometries to be used subsequently. In [6], authors transformed a 3D point cloud into a 3D FE model by generating 2D slices containing bi-dimensional points, form which individual 2D polygonal surfaces where analysed and stacked to generate the aggregated 3D model. In [21], authors conducted a deviation analysis and FE approach to monitor a minaret located in Turkey, where a point-cloud-based mesh was generated, subsequently transforming it to a solid model able to feed structural analysis software. In [9], initial imperfections from a set of steel frames were extracted from raw point cloud and set into a beam-based model defined by the center lines of beam and column elements. The model was set to be embedded in BIM-Enabled platforms for subsequent interoperable structural verification.

The vast number of studies carried out regarding the use of laser scanning techniques has proven its effectiveness for monitoring assets during design, construction, and maintenance stages across multiple disciplines within AEC. Enabling its information in the BIM environment, providing added value to feed calculation models, inadvertently postulate the TLS as a geometrical digital twin (gDT) generator [50,34,27].

2.2 | Applications in education

TLS technologies implemented for educational purposes is still scarce in the AEC academic educational research. Most probably, this is due to the high-cost professional TLS have had in last years. The market price of a professional TLS ranges from 10 to 50 K US dollars. Nevertheless, it is capable of generating a new environment in which several sources of information are concentrated in a 3D virtual model. Recognizably, when used in the classroom, students can be physically present during the generation of point clouds and be subsequently provided with the corresponding results in plain text formats. 3D model learning environments are potential paradigm shifters in teaching and learning process [29]. TLS emerges as one of the technological devices that bring real 3D information from the site to a virtual space that can benefit also civil engineering classrooms.

In [44], researchers presented the advantages of using a TLS to register realistic geometries of structures which are far from university (buildings, bridges, and roads) for further educational use. TLS fosters the capability to visualize and imagine structural elements and details in their construction. Moreover, TLS has been introduced to students in BIM courses [38] where scanning, data processing, and geometric abstraction to a BIM platform were part of the learning process. Its massive use is undermined though, by the cost. One attempt for bypassing costly technologies [5] was presented for the evaluation of more affordable 3D scanning with suitable educational purposes. Authors implemented AR experiences to facilitate students the understanding of complex geometries.

Moreover, the development of online lectures in recent times showed how online sessions should avoid simple replication of face-to-face lessons. In the context of TLS education, one attempt of online immersive classroom is presented in [14], in which authors presented a gamified virtual TLS simulator in a full virtual environment, which allowed to simulate realistic data acquisition, interactively and without the presence of the real device. This allow the user to reproduce virtually a full scanning sequence in the fieldwork and subsequent post-processing.

3 | HANDS-ON DEVELOPMENT OF A LOW-COST LASER SCANNER

TLS is capable of measuring distances between the sensor and an object at a given space. Professional TLS mainly use two different type principle to calculate distance, Time-of-flight (ToF) and Phase Shift (PS) [43].

ToF principle calculates distance by sending a short pulse towards and object while registering the traveling time of the pulse. Thus, the distance (D) is calculated using Equation (1).

$$D = \frac{c}{2} * \Delta t, \quad (1)$$

where c is the light speed and Δt is the elapsed time of the round trip of the pulse.

A PS-based TLS sends an amplitude-modulated sinusoidal laser beam, which measures D by determining the phase difference between the reference and the return signal, using Equation (2).

$$D = \frac{c}{2\mathrm{f}} * \frac{\varphi}{2\pi}, \quad (2)$$

where c is the light speed, f is the modulation frequency, and φ is the phase shift.

The PS principle allows the laser to record high accuracy, ultra-fast data at a medium-range (350 m), while the ToF technique allow to reach longer ranges (km), at a slightly lower rate and with slightly less accuracy. In combination with the measurements of the horizontal orientation angle θ and the vertical inclination φ, the polar coordinate (θ, φ, D) is obtained, which can be subsequently transformed into the cartesian reference system (X, Y, Z), as shown in Figure 1. Angular positions of the laser are accurately obtained within the TLS.

The TLS developed in this study is based on a ToF sensor. The system seeks to replicate a collection of i points with cartesian coordinates (x_i,y_i,z_i) using low-cost, open-source, readily available sensors and actuators controlled by an open-source Arduino Uno break-out board. Namely, a ToF VL53L1X distance measurement sensor (4 m of range), a 6-axis integrated sensor MPU-6050 which includes an accelerometer and gyroscope, and two servomotors were combined for the development of the TLS.

The TLS was firstly designed and manufactured using digital fabrication. The design was entirely done in Rhino 7.0 from scratch and subsequently 3D-printed using a BCN3D Sigma printer. Digital fabrication provides versatility for design since all its components such as sensors, actuators and circuitry can be precisely allocated. Figure 2 shows the final design and the location of the sensors and servomotors. The TLS is divided into two parts: the upper structure and the bottom base. The upper structure is composed of a central box containing the ToF sensor and the MPU-6050. In addition, a shaft, whose rotation its axis is enabled by a servomotor coupled at one of its sides, is contained in the 3D printed structure. The base contains the controller board as well as the second servomotor, which enables the rotation of the whole upper structure about a vertical axis.

The VL53L1X provides a maximum distance D calculated by the ToF that reaches a maximum range 4 m at optimum environmental conditions. The sensor provides a maximum recording rate of 50 Hz. On the other hand, the MPU-6050 accelerometer determines the accelerations acting on the sensor while the gyroscope determines its angular velocity. When fused correctly, these two measurements can determine the attitude of the sensor accurately. The fusion has been performed by a dead-reckoning algorithm along with a complementary filter. This type of data-filter offers good estimation of the position when components rotate, showing errors below one degree for the yaw, pitch, and roll orientations [25,16,28]. In this TLS, servo motors are controlled to reach specific angular positions. The servo located at the base of the TLS is used to determine the angular position θ (rotation about a vertical axis) while the other is used to

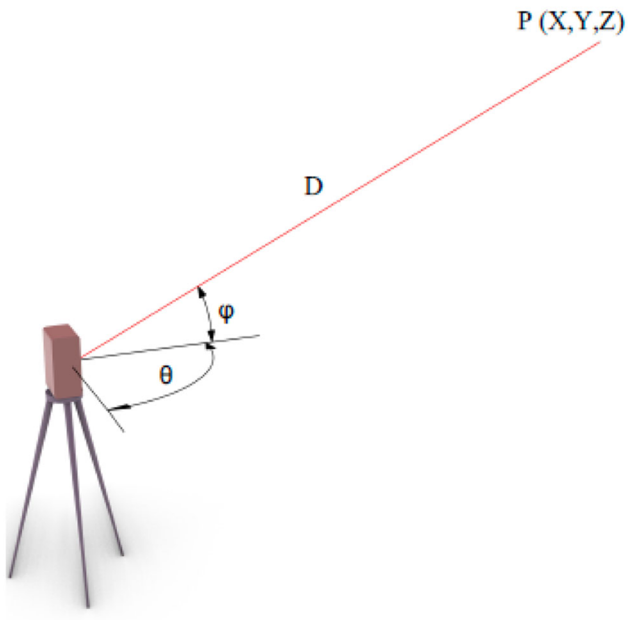


FIGURE 1 Scheme of TLS point recording system. TLS, Terrestrial Laser Scanner

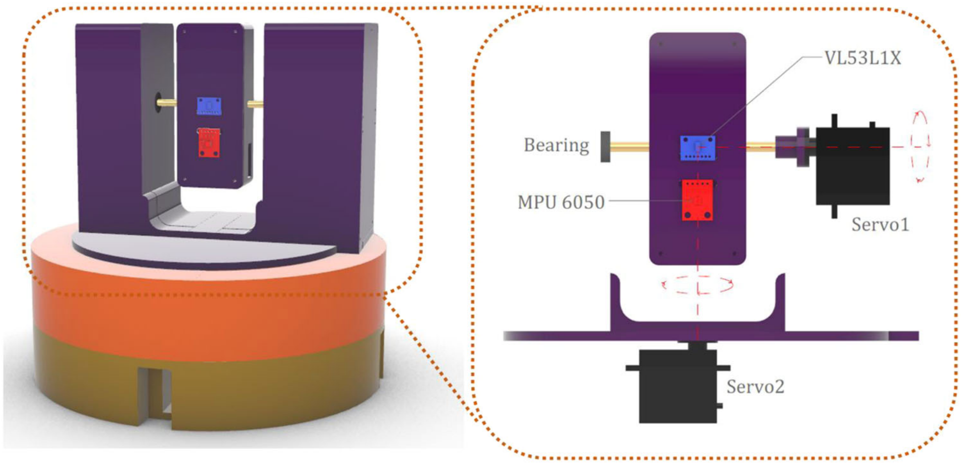


FIGURE 2 TLS 3D model, location of sensors and servos and rotation axes. 3D, three-dimensional; TLS, Terrestrial Laser Scanner

determine φ (rotation about a horizontal axis). Figure 1 illustrates these components.

During the scanning process, points are registered iteratively for a sequence of movements of the servos. At each iteration, the information regarding the position of the servos is obtained. Then, the angle θ is determined by the system and recorded. On the other hand, data from the accelerometer and gyroscope are processed to obtain φ which happens to be a result of the measurement rather than a determined angular position of the servo. Finally, the ToF sensor calculates the range D to the object. Data received from the ToF sensor is filtered according to quality parameters provided by the sensor. The resulting data set $\{\theta_i, \varphi_\mathrm{i}, D_i\}$ for each point i represents polar coordinates. The used microcontroller to acquire this data is open-source and the corresponding programming code is developed by the user. As a result, the data can be transmitted via a vast array of channels to the computer (Serial, Wi-Fi, Ethernet) using different communication protocols (MQTT, HTTP), in different data exchange formats (JSON, XML). Such versatility provided by its open-source nature allows the data set to reach multiple platforms defined by the end-user.

4 | FROM POINT COORDINATES TO COMPUTATIONAL GEOMETRY

At this level, the "as-built" model (virtual) is linked to the printed geometry (physical) through Grasshopper: a visual programming language and environment that runs within Rhinoceros [35] which is used to build generative algorithms for parametric design, generative design, and responsive computer-aided design. The virtual geometrical reproduction of the TLS is constructed in Rhino realistically and then 3D printed. This geometry is provided with the same degrees of freedom of the physical asset. As a result, all potential movements of the TLS are also linked to all potential movements of the virtual model.

On the other hand, any set of measured points are retrieved in the same parametric design platform. Grasshopper represents an interesting educational platform at this level due several facts: it can be connected to sensors directly, it is directly linked to a virtual geometrical space and provides room for programming in manifold languages such as Python, C#, or VB. In addition, a fertile ecosystem of mathematical applications and plugins are nowadays available within the Grasshopper programming community.

Figure 3 shows the flow of information used for the generation of the digital twin of the TLS and of the corresponding generation of point clouds. Data from sensors are transformed to lists containing the spherical coordinates (θ, φ, D) of points. These polar coordinates are transformed to Cartesian coordinates with a Python snippet, applying rotations θ and φ to the corresponding elements in the digital model. The code stores the resulting points {x,y,z} as a list adapted to Rhino.Geometry namespace [https://developer.rhino3d.com/api/RhinoCommon/html/N_Rhino.htm]. The Rhino.Geometry namespace contains a vast amount of geometrical methods of great use in computational geometry. The Geometry namespace is well documented, and it contains geometric types used in Rhino. Examples are lines, curves, meshes, and boundary representations.

5 | SIMPLE APPLICATIONS FOR POINT CLOUD ANALYSIS

Computational geometry (or algorithmic geometry) is at present inherently related to technological developments within AEC. It is applied in multiple disciplines as computer-aided engineering (CAE), computer-aided design (CAD), robotics, or geographic information systems

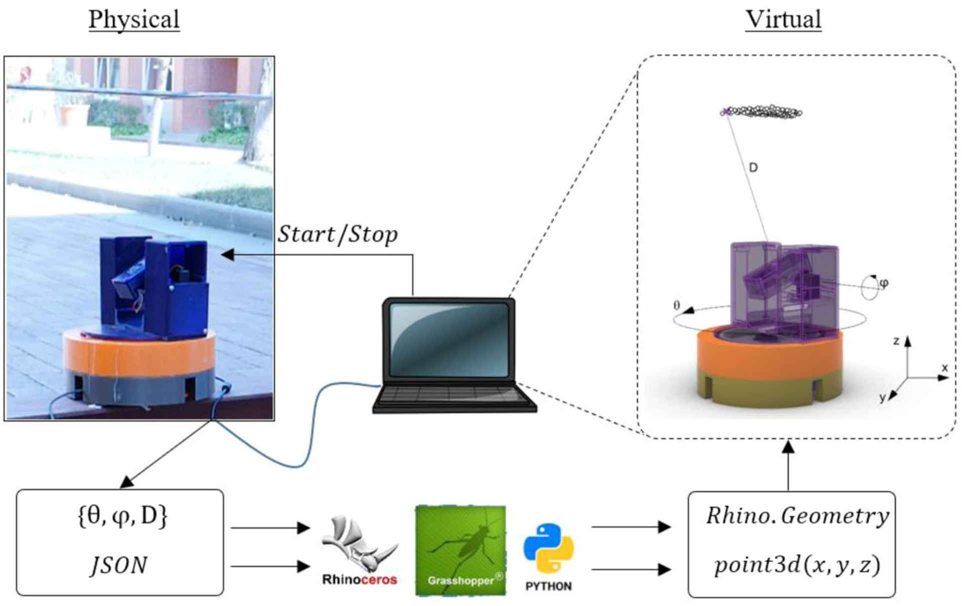


FIGURE 3 From physical to digital. Information flow scheme

(GIS). Students are familiar with the use of software packages where geometric algorithms have an essential contribution. However, in most cases they do not dive into the development, programming, and mathematical comprehension of such algorithms.

Commercial or research-oriented laser scanning technologies often offer mathematical algorithms dedicated to feature extraction from point clouds. Most of them are dedicated to identifying more complex geometrical elements (edges, planes, meshes, objects), to be subsequently used in a huge variety of analyses. In this context, TLS is of great interest in AEC classrooms as data generators for computational geometry case studies. An initiation to geometry analysis in virtual BIM-friendly spaces represents an interesting outcome of this study.

A set of scans on simple geometries has been performed for the generation of guided activities with students. Objects whose shape can be mathematically described are chosen as straightforward examples. The identification of a plane as well as the identification of a sphere are presented herein. This identification is performed using interpolation algorithms embedded within Rhino and Grasshopper. Resulting geometries are visualized and stored as Rhino objects.

5.1 | Identification of a points, lines, and planes

The identification of a plane is a classical exercise of geometry. With three points, a plane characterized by its normal vector is defined. With more than three points, the problem is highly redundant and it needs to be solved using interpolation. Plane interpolation is a key process. A well-stablished plane fitting method is defining a singular value decomposition (SVD) problem.

The plane equation is specified by a point (x, y, z), the director cosines (a, b, c) of the normal to the plane, and an offset d (see Equation 3).

$$ax + by + cz + d = 0. \tag{3}$$

It is known that the best-fit plane contains the centroid of the data (x_c, y_c, z_c). Then, the normal vector (a, b, c) associated to the centroid must be obtained to determine the equation of the plane. To do so, the normal vector is defined as the eigenvector associated to the smallest eigenvalue of the vector B (Equation 4)

$$B = \boldsymbol{A}^T\boldsymbol{A},$$
in which
$$\boldsymbol{A} = \begin{bmatrix} \vdots & \vdots & \vdots \\ x_i - x_c & y_i - y_c & z_i - z_c \\ \vdots & \vdots & \vdots \end{bmatrix}. \tag{4}$$

The **A** is a matrix containing the centered data set of points. By definition, the normal vector (a, b, c) is also the eigenvector associated with the smallest eigenvalue of A. Then, the algorithm to find the best-fit plane to a set of data points can be summarized as follows:

- Calculate the centroid of the point data set (x_c, y_c, z_c)
- Compose the matrix **A**
- Find the eigenvectors and eigenvalues to determine (a, b, c)

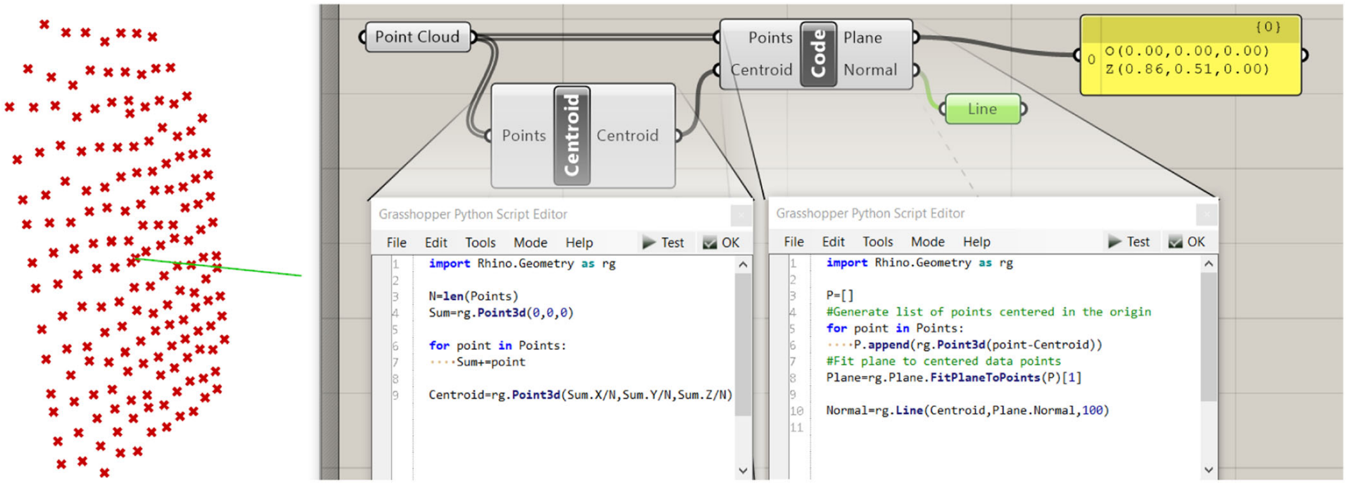


FIGURE 4 Plane fitting using Rhino.Geometry

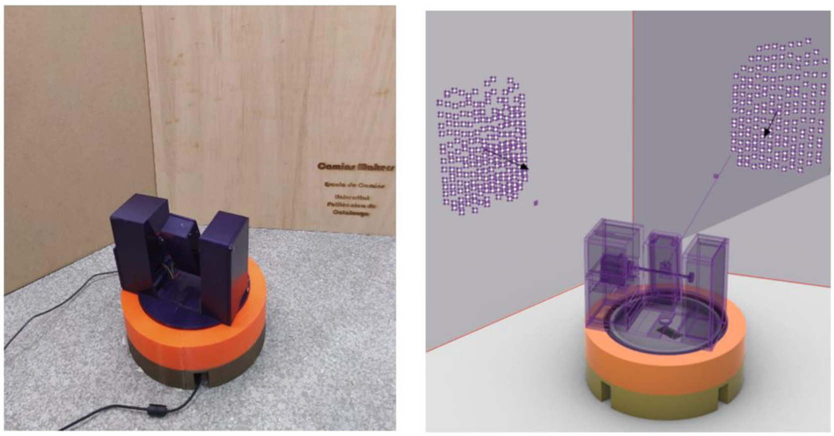


FIGURE 5 Identified corner using low-cost TLS. TLS, Terrestrial Laser Scanner

Figure 4 illustrates how the plane fitting process is performed using with Python scripts using Rhino.Geometry Namespace fitting methods implemented within Grasshopper.

As an example, two wooden plates forming a corner with an unknown angle are used for demonstration. The TLS generates a point cloud for each wooden plate from which a sequential feature extraction is performed: First, planes containing both plates are interpolated from point clouds. Then, the intersection of these planes define a line which features an edge. If this edge is intersected with a horizontal plane passing by the TLS base, the relative coordinate of the corner is obtained. As a result, planes are obtained by eigenvalue extraction, intersection of two planes, or intersection of a plane and an edge are performed using intersection methods available in the Rhino.Geometry namespace, in which all points are initially treated. Figure 5 shows the results obtained after the whole procedure.

5.2 | Identification of a sphere

Increasing the mathematical complexity, the identification of an object is presented. The equation of a sphere is parametrized in a 3D space through the location of its center (x_0, y_0, z_0) and its radius R (see Equation 5)

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = R^2. \tag{5}$$

Center and radius can be interpolated using a least-squares fitting (LSF) algorithm. The algorithm calculates the parameters such that it minimizes the sum of the square of all the distances from the m data points to the fitted sphere (F in Equation 6). The distance between a given point and a sphere is given in terms of the distance from the point to the center of the sphere (r_i) and its radius (R).

$$F = \sum_{i=1}^{m} f_i^2 \quad \text{where} \quad f_i = r_i^2 - R^2. \tag{6}$$

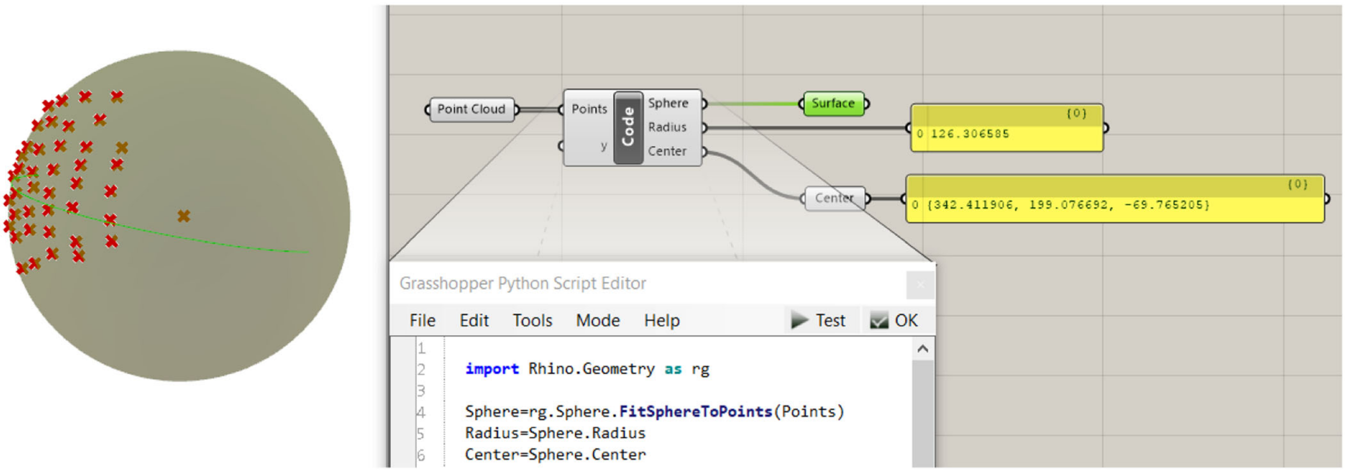


FIGURE 6 Sphere fitting using Rhino.Geometry

Developing f_i we obtain Equation (7):

$$f_i = (x_i - x_0)^2 + (y_i - y_o)^2 + (z_i - z_0)^2 - R^2 = -2x_i x_0 - 2y_i y_0 - 2z_i z_0 + \left(x_0^2 + y_0^2 + z_0^2 - r^2\right). + (x_i^2 + y_i^2 + z_i^2) \quad (7)$$

Thus, making a variable change $\rho = x_0^2 + y_0^2 + z_0^2 - R^2$, f_i is transformed into an over-determined linear system (usually with no solution) where the parameters x_0, y_0, x_0, and ρ are unknowns, as shown in Equation (8)

$$\boldsymbol{A} \bullet u = B,$$

where

$$A = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots \\ 2x_i & 2y_i & 2z_i & -1 \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix}_{mx4}, \quad u = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ \rho \end{bmatrix} and \quad B = \begin{bmatrix} \vdots \\ x_i^2 + y_i^2 + z_i^2 \\ \vdots \end{bmatrix}_{mx1} \quad (8)$$

The optimum set of parameters u^* that minimizes $\|\boldsymbol{A}u - B\|$ can be obtained solving the system of normal equations, shown in Equation (9)

$$\boldsymbol{A}^T \boldsymbol{A} u^* = \boldsymbol{A}^T \boldsymbol{B}. \quad (9)$$

As an example, a sphere with a radius of 125 mm is scanned using the developed TLS. The fitted radius was $R = 126.2$ mm, which imply a difference of 1.2 mm between the measured radius and the mathematically obtained one. Figure 6 shows the sphere fitting process with using Python scripts within the Rhino.Geometry Namespace implemented methods.

Sphere position and dimensions are satisfactorily obtained using a procedure that is mathematically accessible by students of Geomatics. Figure 7 summarizes the results obtained in which the virtual sphere represents the virtual replica of the asset, which has been generated by a TLS, which itself has its digital twin.

6 | THE EDUCATIONAL PROJECT

The development of the TLS belongs to a vaster project for infusing several Construction 4.0-related technologies in AEC classrooms under development in the School of Civil Engineering. The educational project has a broader goal of helping educators of various fields of the Civil Engineering School to embed many of the Construction 4.0 technologies at the core of their corresponding courses. The project has an underlying motto of encompassing mathematics (M), science (S), technologies (T), engineering (E), and art (A) within the development of such activities (STEAM approach). Several STEAM activities are being conceived for different courses [7].

In this particular case, the TLS is aimed at providing a digitally-twinned view of laser scanning for students of Geomatics (2nd year). The application is not limited to this course but it was taken as a good reference since these students get acquainted with this type of equipment throughout the course. Students are exposed to professional TLS and their main capabilities throughout several sessions. The particular session devoted to the developed TLS comes after.

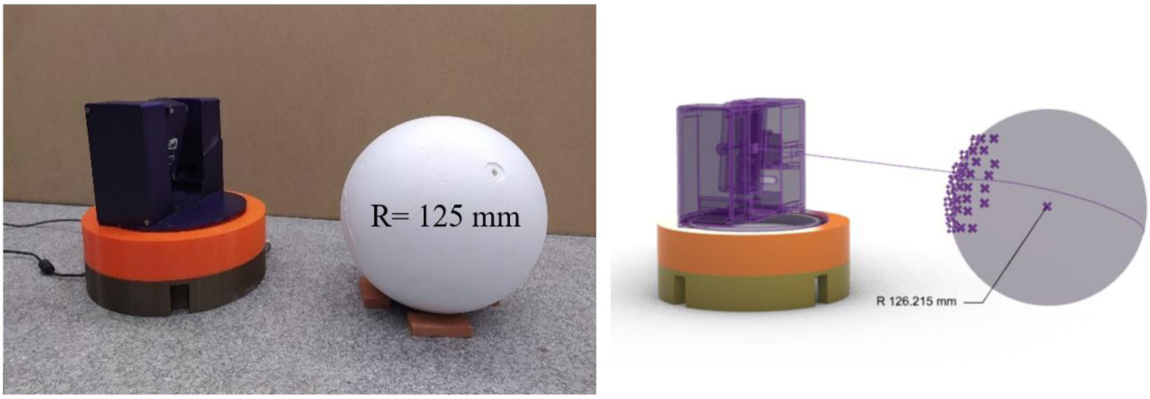


FIGURE 7 Identified sphere using low-cost TLS. TLS, Terrestrial Laser Scanner

The digitally twinned vision of laser scanning has identified novelties of interest in courses of Geomatics and in a broader sense, Civil Engineering:

- To illustrate the measuring principle of sensors using open-source hardware together with the corresponding mathematical and statistical analysis of the results.
- To illustrate the generation and visualization of point clouds in real-time within a CAD environment.
- To illustrate the usage, analysis, and identification of point clouds within BIM-enabled platforms.
- The first edition of these illustrations has included a more general goal: the illustration to students of the potential of more advanced constructional technologies such as cyber-physical systems for monitoring and surveying sites and for obtaining "As-Built" BIM models of real assets.

7 | DISCUSSION

A low-cost digitally twinned TLS has been developed to be used as an educational tool in AEC classrooms. It has been fabricated digitally using generative design and materialized physically using a 3D printer. It has been provided with low-cost sensors and actuators for measuring. Data from all sensors has been combined to create point clouds that are transmittable to the same generative, parametric design tools in which it was created. Versatile data flows are conceived for proper digital twinning. Thus, the virtual twin of the model has been linked to this incoming data from sensors to generate point clouds embedded in this CAD environment, where geometries can be fully used, analyzed, and manipulated by the user. This represents a novelty for AEC classrooms. Students can follow in real-time the information flow from sensors to point clouds. Cognition is triggered at this point.

Moreover, enabling these point cloud data to be manipulated in frequently used CAD software packages represents an ideal creativity environment for AEC students. Data retrieval using sensors, device programming, networking, and generation of visual interfaces are new concepts that generate high interest to students as well as an educational path towards the digital transformation of the sector.

In early applications of the tool in Bachelor and Master courses of Civil Engineering, several conclusions are pointed out:

- From the perspective of measurement, presenting the low-cost TLS, students are acquainted with laser scanner technologies and comprehend their measuring principles. Also, they learn how data is obtained, combined, and transferred to a visual interface in a real-time data acquisition environment. On the other hand, students become aware of the limitations of the tool via statistical analysis.
- From the perspective of real-time visualization and digital twinning of the asset, fusing TLS data within a computational geometry tool in real-time shows many advantages for understanding measurement in real-time. The presented TLS allows virtualizing and visualizing 3D information synchronously. During the presentation of the TLS to the students in the first edition, an active debate on results was developed. It showed a profound implication of them when scrutinising the tool, understanding the professional device used in the classroom as well. The performance of both TLS in terms of accuracy and capacity was clear to students. From the debate, the key takeaway that can be extracted is their engagement when visualizing results in real-time. The synchronous nature of the visualization provides a seamless interface which is ideal for opening debates in the classroom.

- From the perspective of computational geometry, identification of simple geometries has been performed implementing algorithms to process point cloud information. This process enhances students' spatial vision capabilities and allows initiating one promising skill for their professional Construction 4.0 future, which is related to geometrical identification using TLS. Also, it allows to comprehend and utilize mathematical concepts from analytic geometry learned in previous courses with practical applications. During the process, students receive continuous visual feedback, which enhances engagement, error detection and improves their degree of satisfaction. Once geometries are computationally tractable, instructors can focus on the scanning routines and the resulting 3D information, zooming out from the mathematical processes and data flows required to manipulate raw point clouds.

8 | PROPOSAL FOR THE USE OF TLS IN AEC CLASSROOMS

The developed low-cost TLS is especially interesting to be introduced to AEC students in courses where spatial data mining and data processing are of relevant importance. In this study, the tool is presented to students as a remote sensing tool that generates 3D point clouds. In its 2020–2021 edition, students that are enrolled in two courses, namely, "Experimental Techniques in Construction" of the Master's degree on Structural and Construction Engineering and "Geomatics," of the new degree of Technologies for Civil Engineering (e.g., Figure 8).

For the former, students become acquainted with different experimental techniques in construction after a "hands-on" introduction to the use of sensors, data acquisition systems, and graphical user interfaces. Furthermore, they can transfer the data into a graphical user-interface, generating a connection from the physical to the virtual world [8,10,11]. For the latter, students treat TLS in manifold applications ranging from surveying to landslides.

At this level, two aspects of relevance must be presented in AEC classrooms:

- Explanation of the measuring principles (sensors)
- Explanation of the digital twinning of the asset and the corresponding real-time visualization of point cloud generation (user interfaces).
- Explanation of identification of geometries (maths).

In more pedagogical terms, this experience can be embedded in civil engineering classrooms using multiple approaches:

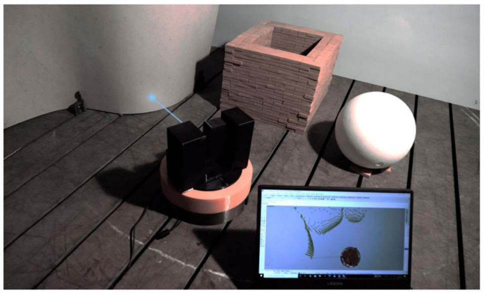


FIGURE 8 Laser scanner in action during a demo session in "Experimental Techniques in Construction"

- A demonstrative intervention (3 h class). the digitally twinned laser scanner is introduced to students, who are acquainted with the measurement principles of commercial TLS as well with resulting point clouds. Additionally, students are introduced to sensors and to concepts such as cyber-physical systems, digital twins, smart infrastructures.
- A generator of identification exercises (autonomous work). Real geometries can be scanned and subsequently identified by students using computational geometry tools. This part would also allow presenting measurements of geometries in the classroom to big groups and then, providing the results in the form of point cloud directly to students for further treatment.
- A developmental hands-on course (25 h–1 ECTS). Students with basic knowledge about Rhino-grasshopper and sensors manipulation using Arduino participate in a hands-on project, where they are provided with intermediate programming skills to a digitally twinned terrestrial laser scanner.

9 | CONCLUSIONS

In AEC, TLS emerges as a new advanced remote-sensing tool capable of registering accurate 3D information from real assets in the form of point clouds, which is increasingly necessary in the construction site. Educationally speaking, an integration of TLS in the classroom has not yet been possible due to economic constraints. In this project, a proof-of-concept of a digitally twinned TLS has been built from scratch using generative design, digital fabrication, low-cost sensors, and mathematical manipulation of results in real-time. The artefact as well as its computer application provides point cloud of physical objects that are subsequently identified and twinned in a virtual space by students. Simple geometries can be easily identified and visualized in real-time by the users.

The educational proof-of-concept of this TLS has already provided a digitally-twinned view of laser scanning for students at Bachelor and Master levels at the School of Civil Engineering in Barcelona, at the UPC-Barcelona-Tech. In such courses, the present digitally twinned vision of laser scanning has thus three identified educational uses: (i) illustration of the measuring principle of sensors, (ii) illustration of the generation and visualization of point clouds in real-time within a virtual environment, and (iii) illustration of the usage, analysis, and identification of point clouds. In future editions, a more systematic use of such device is expected in larger groups in which several devices are simultaneously available.

The first edition of these illustrations has also included a subsequent, more general goal: the illustration to students of all these concepts with accessible technological tools is expected to enlarge their vision to more advanced constructional technologies such as cyber-physical systems for monitoring and surveying sites and for obtaining "As-Built" BIM models of real assets. Since new and emerging technologies in the AEC sector are transforming and creating new opportunities, the need of infusing AEC curricula according to current technological progress becomes a cornerstone debate. In Construction 4.0, advances in Industrial Construction (Robotics and Digital Fabrication), Cyber-Physical Systems (Digital Twins or Smart Infrastructure), and Digital Technologies (BIM, and Extended Realities) represent the advent of a new era in the field. To adopt technology, new professionals require understanding of breakthrough technologies to remain competitive, independent, and technologically sovereign.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Rolando Chacón http://orcid.org/0000-0002-7259-5635

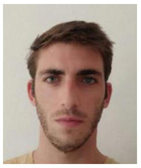
REFERENCES

1. A. Agirbas, *Teaching construction sciences with the integration of BIM to undergraduate architecture students*, Front. Architect. Res. **9** (2020), no. 4, 940–950.
2. T. Akyazi, I. Alvarez, E. Alberdi, A. Oyarbide-Zubillaga, A. Goti, and F. Bayon, *Skills needs of the civil engineering sector in the European union countries: current situation and future trends*, Appl. Sci. **10** (2020), no. 20, 7226.
3. F. Bosché, A. Guillemet, Y. Turkan, C. T. Haas, and R. Haas, *Tracking the built status of MEP Works: assessing the value of a Scan-vs-BIM system*, J. Comput. Civil Eng. **28** (2014), no. 4, 05014004. https://doi.org/10.1061/(asce)cp.1943-5487.0000343
4. I. Brilakis, M. Lourakis, R. Sacks, S. Savarese, S. Christodoulou, J. Teizer, and A. Makhmalbaf, *Toward automated generation of parametric BIMs based on hybrid video and laser scanning data*, Adv. Eng. Inform. **24** (2010), no. 4, 456–465.
5. J. D. Camba, A. B. De Leon, J. De La Torre, J. L. Saorin, and M. Contero, *Application of low-cost 3D scanning technologies to the development of educational Augmented Reality content*. Proceedings—Frontiers in Education Conference, FIE, 2016. pp. 1-6 https://doi.org/10.1109/FIE.2016.7757673
6. G. Castellazzi, A. M. D'Altri, G. Bitelli, I. Selvaggi, and A. Lambertini, *From laser scanning to finite element analysis of complex buildings by using a semi-automatic procedure*, Sensors **15** (2015), no. 8, 18360–18380. https://doi.org/10.3390/s150818360
7. R. Chacón, *Designing construction 4.0 activities for AEC classrooms*, Buildings **11** (2021), no. 11, 511.
8. R. Chacón, D. Codony, and Á. Toledo, *From physical to digital in structural engineering classrooms using digital fabrication*, Comput. Appl. Eng. Educ. **25** (2017), no. 6, 927–937. https://doi.org/10.1002/cae.21845
9. R. Chacón, C. Puig-Polo, and E. Real, *TLS measurements of initial imperfections of steel frames for structural analysis within BIM-enabled platforms*, Automat. Constr. **125** (2021), 103618. https://doi.org/10.1016/j.autcon.2021.103618
10. R. Chacón, H. Posada, Á. Toledo, and M. Gouveia, *Development of IoT applications in civil engineering classrooms using mobile devices*, Comput. Appl. Eng. Educ. **26** (2018), no. 5, 1769–1781. https://doi.org/10.1002/cae.21985
11. R. Chacón, M. Sánchez-Juny, E. Real, F. X. Gironella, J. Puigagut, and A. Ledesma, *Digital twins in civil and environmental engineering classrooms*. Proc., EUCEET 2018-4th international conference on civil engineering education: challenges for the third millennium, 2018, pp. 290–299.
12. E. Che, J. Jung, and M. J. Olsen, *Object recognition, segmentation, and classification of mobile laser scanning point clouds: a state of the art review*, Sensors (Switzerland) **19** (2019), no. 4. https://doi.org/10.3390/s19040810
13. S. Chen, H. Liu, Z. Feng, C. Shen, and P. Chen, *Applicability of personal laser scanning in forestry inventory*, PLoS ONE **14** (2019), no. 2, 1–22. https://doi.org/10.1371/journal.pone.0211392
14. M. Chizhova, D. Popovas, D. Gorkovchuk, J. Gorkovchuk, M. Hess, and T. Luhmann, *Virtual terrestrial laser scanner simulator for digitalization of teaching environment: concept and first results. International Archives of the Photogrammetry, Remote Sensing and Spatial*, Information Sciences-ISPRS Archives **43** (2020), no. B5, 91–97. https://doi.org/10.5194/isprs-archives-XLIII-B5-2020-91-2020
15. S. A. Gargoum and L. Karsten, *Virtual assessment of sight distance limitations using LiDAR technology: automated obstruction detection and classification*, Automat. Constr. **125** (2021), 103579. https://doi.org/10.1016/j.autcon.2021.103579
16. P. Gui, L. Tang, and S. Mukhopadhyay, MEMS based IMU for tilting measurement: comparison of complementary and kalman filter based data fusion, 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA), Auckland, New Zealand, 2015, pp. 2004-2009, https://doi.org/10.1109/ICIEA.2015.7334442
17. B. Riveiro and R. Lindenbergh, eds. *Laser scanning: an emerging technology in structural engineering*, 1st ed. CRC Press, 2019 https://doi.org/10.1201/9781351018869

18. J. Jung, S. Hong, S. Jeong, S. Kim, H. Cho, S. Hong, and J. Heo, *Productive modeling for development of as-built BIM of existing indoor structures*, Automat. Constr. **42** (2014), 68–77. https://doi.org/10.1016/j.autcon.2014.02.021
19. M. K. Kim, J. P. P. Thedja, and Q. Wang, *Automated dimensional quality assessment for formwork and rebar of reinforced concrete components using 3D point cloud data*, Automat. Constr. **112** (2020), 103077. https://doi.org/10.1016/j.autcon.2020.103077
20. P. Kim, J. Chen, and Y. K. Cho, *Automated point cloud registration using visual and planar features for construction environments*, J. Comput. Civil Eng. **32** (2017), no. 2, 1–13.
21. M. Korumaz, M. Betti, A. Conti, G. Tucci, G. Bartoli, V. Bonora, A. G. Korumaz, and L. Fiorini, *An integrated Terrestrial Laser Scanner (TLS), Deviation Analysis (DA) and Finite Element (FE) approach for health assessment of historical structures. A minaret case study*, Eng. Struct. **153** (2017), 224–238. https://doi.org/10.1016/j.engstruct.2017.10.026
22. F. Leite, Y. Cho, A. Behzadan, S. Lee, S. Choe, Y. Fang, R. Akhavian, and S. Hwang, *Visualization, information modeling, and simulation: grand challenges in the construction industry*, J. Comput. Civil Eng. **30** (2016), no. 6, 04016035. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000604
23. F. Li and M. K. Kim, *Mirror-aided registration-free geometric quality inspection of planar-type prefabricated elements using terrestrial laser scanning*, Automat. Constr. **121** (2021), 103442. https://doi.org/10.1016/j.autcon.2020.103442
24. H. Li, C. Zhang, S. Song, S. Demirkesen, and R. Chang, *Improving tolerance control on modular construction project with 3d laser scanning and BIM: a case study of removable floodwall project*, Appl. Sci. **10** (2020), no. 23, 1–21. https://doi.org/10.3390/app10238680
25. J. F. Li, Q. H. Wang, X. M. Liu, and M. Y. Zhang, *An autonomous waist-mounted pedestrian dead reckoning system by coupling low-cost MEMS inertial sensors and GPS receiver for 3D urban navigation*, J. Eng. Sci. Technol. Rev. **7** (2014), no. 1, 9–14. https://doi.org/10.25103/jestr.071.02
26. C. Liu, N. Li, H. Wu, and X. Meng, *Detection of high-speed railway subsidence and geometry irregularity using terrestrial laser scanning*, J. Surv. Eng. **140** (2014), no. 3, 04014009. https://doi.org/10.1061/(asce)su.1943-5428.0000131
27. R. Lu and I. Brilakis, *Generating bridge geometric digital twins from point clouds*. Proceedings of the 2019 European Conference on Computing in Construction, 2019. https://doi.org/10.35490/ec3.2019.182
28. R. S. McGinnis, S. M. Cain, S. P. Davidson, R. V. Vitali, S. G. McLean, and N. C. Perkins,*Validation of complementary filter based IMU data fusion for tracking torso angle and rifle orientation*. Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition. Vol. **3**, 2014, pp. 14–20. https://doi.org/10.1115/IMECE2014-36909
29. P. Meadati, and A. Akhnoukh, *3D scans—a new teaching tool in construction education*, Collaboration and integration in construction, engineering, management and technology (S. M. Ahmed, P. Hampton, S. Azhar, and A. D. Saul, eds.) 2019, pp. 217–222.
30. L. Noordermeer, R. Økseter, H. Ole Ørka, T. Gobakken, E. Næsset, and O. M. Bollandsås, *Classifications of forest change by using bitemporal airborne laser scanner data*, Remote Sens. **11** (2019), no. 18, 2145. https://doi.org/10.3390/rs11182145
31. J. M. Pearce, *Building research equipment with free, open-source hardware*, Science **337** (2012), no. 6100, 1303–1304.
32. N. Puri and Y. Turkan, *Bridge construction progress monitoring using lidar and 4D design models*, Automat. Constr. **109** (2020), 102961. https://doi.org/10.1016/j.autcon.2019.102961
33. C. Rausch and C. Haas, *Automated shape and pose updating of building information model elements from 3D point clouds*, Automat. Constr. **124** (2021), 103561. https://doi.org/10.1016/j.autcon.2021.103561
34. C. Rausch, R. Lu, S. Talebi, and C. Haas, *Deploying 3D scanning based geometric digital twins during fabrication and assembly in offsite manufacturing*, Int. J. Constr. Manag. (2021), 1–14. https://doi.org/10.1080/15623599.2021.1896942
35. Rhinoceros v7.0. Mcneel Associates. https://www.rhino3d.com/
36. G. Rocha, L. Mateus, J. Fernández, and V. Ferreira, *A scan-to-BIM methodology applied to heritage buildings*, Heritage **3** (2020), no. 1, 47–67. https://doi.org/10.3390/heritage3010004
37. A. Sawhney, M. Riely, and J. Irizarry, Construction 4.0: An Innovation Platform for the Built Environment, *First Edition*., Routledge, London, UK, 2020.
38. H. A. Shanbari, N. M. Blinn, and R. R. Issa, *Laser scanning technology and BIM in construction management education*, J. Inf. Technol. Constr. **21** (2015), 204–217.
39. J. Shao, W. Zhang, N. Mellado, P. Grussenmeyer, R. Li, Y. Chen, P. Wan, X. Zhang, and S. Cai, *Automated markerless registration of point clouds from TLS and structured light scanner for heritage documentation*, J. Cult. Herit. **35** (2019), 16–24. https://doi.org/10.1016/j.culher.2018.07.013
40. K. T. Slattery, D. K. Slattery, and J. P. Peterson, *Road construction earthwork volume calculation using three-dimensional laser scanning*, J. Surv. Eng. **138** (2012), no. 2, 96–99. https://doi.org/10.1061/(asce)su.1943-5428.0000073
41. M. Soilán, A. Sánchez-Rodríguez, P. Del Río-Barral, C. Perez-Collazo, P. Arias, and B. Riveiro, *Review of laser scanning technologies and their applications for road and railway infrastructure monitoring*, Infrastructures **4** (2019), no. 4, 1–29. https://doi.org/10.3390/infrastructures4040058
42. E. Sotelino, V. Natividade, and C. Saad Travassos do Cormo, *Teaching BIM and its impact on Young Professionals*, J. Civil Eng. Educ. **146** (2020), no. 4, 05020005. https://doi.org/10.1061/(ASCE)EI.2643-9115.0000019
43. C. Suchocki, *Comparison of time-of-flight and phase-shift TLS intensity data for the diagnostics measurements of buildings*, Materials **13** (2020), no. 2, 353. https://doi.org/10.3390/ma13020353
44. E. Szafranko and J. A. Pawlowicz, *The application of a 3D laser scanner in contemporary education of civil engineers students*, IOP Conf. Series: Mater. Sci. Eng. **251** (2017), no. 1, 012001. https://doi.org/10.1088/1757-899X/251/1/012001
45. C. Wang, C. Wen, Y. Dai, S. Yu, and M. Liu, *Urban 3D modeling with mobile laser scanning: a review*, Virtual Reality Intell Hardware **2** (2020), no. 3, 175–212. https://doi.org/10.1016/j.vrih.2020.05.003
46. L. Wang, M. Huang, X. Zhang, R. Jin, and T. Yang, *Review of BIM adoption in the higher education of AEC disciplines*, J. Civil Eng. Educ. **146** (2020), no. 3, 06020001. https://doi.org/10.1061/(ASCE)EI.2643-9115.0000018

47. Q. Wang and M. K. Kim, *Applications of 3D point cloud data in the construction industry: a fifteen-year review from 2004 to 2018*, Adv. Eng. Inf. **39** (2019), 306–319. https://doi.org/10.1016/j.aei.2019.02.007
48. W. Wang, W. Zhao, L. Huang, V. Vimarlund, and Z. Wang, *Applications of terrestrial laser scanning for tunnels: a review*, J. Traffic Transp. Eng. **1** (2014), no. 5, 325–337. https://doi.org/10.1016/S2095-7564(15)30279-8
49. Y. Yan and J. F. Hajjar, *Automated extraction of structural elements in steel girder bridges from laser point clouds*, Automat. Constr. **125** (2021), 103582. https://doi.org/10.1016/j.autcon.2021.103582
50. C. Ye, L. Butler, C. Bartek, M. Iangurazov, Q. Lu, A. Gregory, and M. Girolami,A *digital twin of bridges for structural health monitoring*. Proceedings of the 12th international workshop on structural health monitoring. Stanford University, 2019.
51. L. Yuan, J. Guo, and Q. Wang, *Automatic classification of common building materials from 3D terrestrial laser scan data*, Automat. Constr. **110** (2020), 103017. https://doi.org/10.1016/j.autcon.2019.103017
52. F. Zamora-Polo, A. Luque-Sendra, F. Aguayo-González, and J. Sánchez-Martín, *Conceptual framework for the use of building information modeling in engineering education*, Int. J. Eng. Educ. **35** (2019), no. 3, 744–755.
53. D. Zhang, X. Xu, H. Lin, R. Gui, M. Cao, and L. He, *Automatic road-marking detection and measurement from laser-scanning 3D profile data*, Automat. Constr. **108** (2019), 102957. https://doi.org/10.1016/j.autcon.2019.102957
54. D. Zhao, *Peer pressure in BIM-based collaboration improves student learning*, J. Civil Eng. Educ. **147** (2020), no. 2, 04020019. https://doi.org/10.1061/(ASCE)EI.2643-9115.0000038
55. X. Zhou, J. Liu, G. Cheng, D. Li, and Y. F. Chen, *Automated locating of replaceable coupling steel beam using terrestrial laser scanning*, Automat. Constr. **122** (2021), 103468. https://doi.org/10.1016/j.autcon.2020.103468

AUTHOR BIOGRAPHIES



Carlos Ramonell, PhD Student at the Department of Civil and Environmental Engineering currently developing research on automated pipelines of information from physical to virtual realms in the construction sector in the form of digital twins.

Rolando Chacón, Associate Professor at the Department of Civil and Environmental Engineering. Active researcher in the field of structural engineering as well as in the field of digital twins and Construction 4.0 techniques in both research and education.

How to cite this article: C. Ramonell, and R. Chacón, *Open-source Terrestrial Laser Scanner for the virtualization of geometrical entities in AEC classrooms*, Comput. Appl. Eng. Educ. (2022), 1–13. https://doi.org/10.1002/cae.22499