STEAM activities for civil engineering curricula. From Calculus to Digital Twins

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***Abstract*—This full paper describes a set of pedagogical activities designed for students of all academic years in civil engineering programs. The pedagogical project has a twofold aim: i) exposing civil engineering students to Construction 4.0-related technologies and ii) fostering motivation and creativity among students by including STEAM by-design. In this paper, a set of STEAM activities designed for selected courses of this new degree in Civil Engineering Technologies is described. These activities are designed for the sake of promoting Construction 4.0-related skills to broad audiences in civil engineering by means of a learning pathway. This pathway is conceived using several branches of Construction 4.0. Namely, Industrial Production, Cyber-Physical Systems and Digital Technologies. All activities are designed using accessible and affordable Hardware and Software for scalability purposes. The selection includes a broad range of topics that are routinely taught in all academic years (1st to 4th) of the new degree.**

Keywords—STEAM, Civil Engineering, Construction 4.0

I. Introduction

Engineering educators are continuously challenged for cultivating technical competencies in students that are faced to a continuously changing professional sector. The field of civil engineering faces grand challenges when it comes to digitalization of the sector. As a result, the present generation of civil engineering students encounter massive advances in sensing, information and computing technologies that continuously provide to the Architecture, Engineering and Construction sector (AEC) ways for dealing with the large variety of technical information at all project stages. The whole project life cycle, from conception, design, construction, to operation and maintenance is continuously infused with a rising amount of ubiquitously generated and distributed data. New sensors, new forms of visualization and new interoperable design tools are increasingly intertwined. The manifold forms of visualization, information modelling and simulation (VIMS) are called to be part of centralized information hubs in which all stakeholders establish data flow seamlessly [1].

Instrumentation, data-gathering, sensing, automation and construction robotics in civil engineering education has been pinpointed as a need for several years [2][3]. Nevertheless, civil engineering schools worldwide has not yet massively integrated instrumentation, sensing technologies, automation and data integration within formal curricula. Even though technologies have allowed proper implementation of laboratory-based environments, their cost have been prohibitive for a massive application at undergraduate levels. As a result, academic experiences in which attempts to infusing such technologies in AEC education are scarce.

Education-wise, a laboratory-based pedagogy in science and engineering has been one of the greatest and most effective tools [4]. Physical experiences foster cognition and provide effective skill acquisition. Teaching labs are used in civil engineering to let the students discover and measure phenomena. Classical subjects are often provided with laboratory sessions in which students manipulate samples and develop reports on experiments in which magnitudes with practical applications are characterized. However, equipment is often expensive and limited. Consequently, students seldom develop their own measurement devices. In last years though, with the advent of low-cost electronics, the development of open-source labs has become plausible in several fields [5][6]. In recent years with the disruption of IoT, several AEC academic examples of implementation of low-cost systems in cities [7], buildings [8] water supply chain [9] or monitoring of historical constructions [10] have been published. When it comes to education, the development of IoT devices in civil engineering classrooms shows great potential due to the increasing affordability, both technical and economical [11]. AEC colleges and universities are increasingly infusing electronics, fabrication, sensors and coding. Examples in the fields of structural analysis [12-13], structural dynamics [14-15] and responsive architecture [16] show the great potential in many of the disciplines of the AEC sector.

The paper describes a set of pedagogical activities designed for students of civil engineering bachelor degrees at the School of Civil Engineering in Barcelona, Spain. The pedagogical project has a twofold aim: exposing civil engineering students to Construction 4.0-related technologies and ii) fostering motivation and creativity among students by including STEAM by-design. The activities are focused on the development of a set of workshops that erect a personal learning path for students of the School. Some of those workshops have already been systematically implemented in recent years. Some other are designed but not yet implemented. The paper shows the key takeaways of an educational project developed at the School of Civil Engineering aimed at infusing Science, Technology, Engineering, Arts and Mathematics throughout the development of a new degree in Civil Engineering Technologies.

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II. FRAMEWORK OF THE DESIGNED LEARNING PATH

All technological advances in the Architecture, Engineering and Construction sector (AEC) are presently shaping the framework Construction 4.0, a term coined some years ago which relates the Fourth Industrial Revolution (4IR) and its resulting network Industry 4.0, to the built environment. The built environment sector is reaching maturity for leapfrogging to more efficient production, business models and overall, value chains. Such a transformation is possible through existing and emerging technologies within Industry 4.0. According to Sawney et al. [17], in AEC sector, the confluence of emerging technologies together with the needs of the sector, is generating a framework in which three themes can be identified: i) Industrial Production (prefabrication, additive manufacturing, offsite manufacture and robotic assembly), ii) cyber-physical systems (robots, digital twins, sensors-connectivity-actuators) and digital technologies (BIM, extended realities, interoperability, cloud computing, blockchain, AI, computer vision, etc.).

The field of civil engineering is expanding beyond the traditional design and decision-making process. As global challenges continue, civil engineering requires innovation to maintain competitiveness. New social, environmental and economic models and scenarios pose significant challenges for the adaptation of current structures and systems, mobility management, transport and logistics, large infrastructure management, water supply, energy sources, waste reduction and environmental protection. The world is changing and the need of skillful professionals who are able to provide innovative and creative solutions from a global perspective using the knowledge of the twenty-first century is a must. Civil engineering is an essential part of this development towards the societies of the future. It contributes to the improvement of people's quality of life, environmental protection and economic growth, which is nowadays and historically aligned with the SDG. In order to contribute to this adaptation, a new degree on Civil Engineering Technologies has been recently implemented.

A personal learning path is a learner-centered approach that emphasizes learner-specific goals and objectives, as well as preferences that a learner elects on their own. Students comprehend their personal learning pathways through several ways such as: i) the identification of elective courses through preference of topics that are the most relevant to student's current or future professional activity, ii) use of side-courses, workshops, capstones, hackathons or iii) development of internships and academic exchanges. Many other ways may also shape a unique path, personalized, which is outside of the regulated formal learning process [18]. On the other hand, the unexpected disruption that generated the global pandemics has changed profoundly the perception of learners towards content acquisition. The potential of online learning embeddedness in formal education leapfrogged. The post-pandemics educational scene will inevitably blend in-Campus and online learning which may also contribute to the personal choices that will shape all individual learning paths. Presently, the availability of educational online content, though sometimes disaggregated, is incredibly fertile for committed learners.

Figure 1 displays the framework of the designed learning path. The chosen degree is Technologies in Civil Engineering, which is a four-year long program recently implemented at our School. Students in this new degree are in their 2^{nd} academic year by the 2020-2021 program. The framework encompasses cornerstone projects, capstone projects and a series of workshops. Over the past two years, a cornerstone project on interactive programming of mathematical functions have been successfully implemented. More than 150 students have already developed a coding activity in the context of Calculus, which is a 1^{st} year compulsory topic. Another cornerstone project has already been prepared and implemented. This project is related to computational geometry and it is meant to introduce students to coding analytical geometry within virtual spaces. Both activities present an intertwined link between Maths (M) and Arts (A) throughout visual programming. It is worth pointing out that the former has already been infused within formal courses whereas the latter has only been developed as optional.

Then a series of activities for subsequent years have been identified, planned, developed. Some of them have been implemented for several years at Master levels whereas other are recently developed. These activities are initially designed as optional. The personal learning path is conceived for following the latest technological trends that are referred to as Contruction 4.0. Smart infrastructure, Digital Fabrication, Automation and Robotics and Extended Realities are included. The Building Information Modelling layer is included in most of the workshops. By the end of the degree, capstones projects with advanced applications of cyber-physical systems in construction, namely, digital twins are planned as the final activity of this personal learning path. It is worth pointing out that the workshops are not necessarily meant to follow the structure of the 2^{nd} and 3^{rd} academic years.

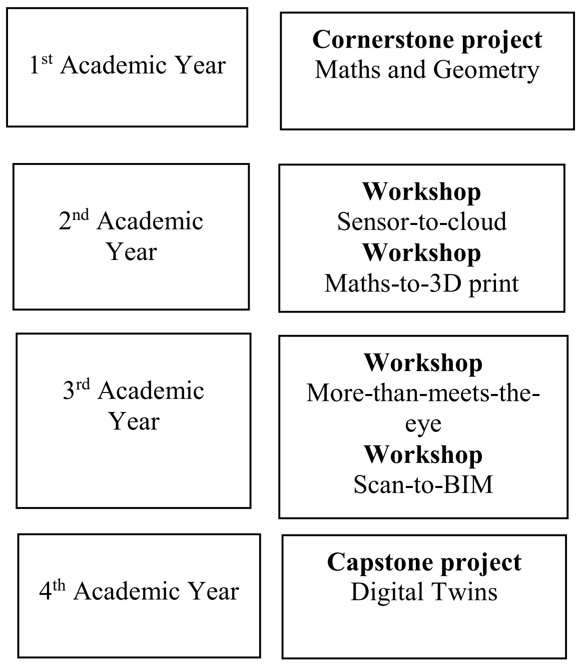

Fig. 1. Organization of the activities in a Construction 4.0 framework

III. CORNERSTONE PROJECTS. MATHS AND GEOMETRY

The cornerstone projects are established as activities related to Calculus and Computational Geometry. These activities are conceived for the sake of exposing our civil engineering students to the development of computational applications using basic concepts of mathematics and geometry.

The first project deals with an activity in which functions, derivatives and an introductory programming challenge are intertwined. Applied introductory programming are always useful for civil engineering students due to their uneven prior acquaintance with coding skills. The project is aimed at reinforcing concepts of differentiation throughout a hands-on coding activity. The formal Calculus syllabus (M) including derivatives is illustrated by students by designing a beautiful visual application (A). Students enrolled in the course are given an optional yet graded task. The challenge of the activity is: For a given implicit function, an interactive visual application must be developed. This application requires i) drawing the curve and ii) drawing a tangent line to the curve as the mouse pointer is placed on any of its points (x,y). The first requirement is a straightforward static code in which points of coordinates (x,y) are plotted in a Canvas. The second requirement is more advanced dynamic interactive code that presumes an adequate use of time and space within the snippet. Students are entitled to use creativity and beauty in the development of such applications by plotting moving primitives (points, lines, rectangles, circles, triangles) in a 2D space with a creative formatting.

The activity has already been embedded in regular courses of Calculus. These students often have no prior knowledge in coding. The chosen tool is the platform Processing [19]. Processing is a programming language, development environment, and online community that promotes coding literacy within the visual arts as well as visual literacy within coding. The platform is considerably used by artists for the development of object-oriented, event-driven interactive applications in a diversity of realms such as mapping, music, animation, physics or installations. For the depicted activity, the full capability of the platform may seem overwhelming but its simplicity (and further potential in other workshops) gave to the facilitators strong reasons to use it. The language syntax is identical to Java but with a few modifications. Time and space are blended together intuitively. Lessons were conceived for students with no prior knowledge in coding visual applications and were structured in six sections as shown in Table 1.

Table 1. Structure of the lessons for the cornerstone project. Interactive programming

The Canvas The unit: Pixels The coordinates	Frames per second Milliseconds Delay	Points, Lines, Vectors Rectangles,Squares, Circles, Triangles
Space	**Time**	**Primitives**
Data types If/then/Else, For, While Functions	Background, RGB, Color, Fill, Stroke	Translation Rotation
Basic instructions	**Format**	**Movement**

A basic structure of a visual program in Processing follows two functions: i) setup(), in which aspects such as size of the Canvas (in pixels), definition of path to files or to serial communication and other fixed parameters are established. This function executes once and must contain not invariable parameters. Subsequently, ii) the function draw() which runs indefinitely. It runs according to the order of written commands from top to bottom and repeats in a loop. The speed of execution between each loop can be regulated by using the delay command.

The first edition of the activity was set during the 2019-2020 academic year for 1st year students of Calculus at Bachelor levels. As documentation, a set of pdf files as well as an online video tutorial are given to the students. Other online resources available are recommended. Unfortunately, face-to-face tutorships were not allowed during this edition due to Health Regulations in the country. As a result, only web meetings were held during the experience. The second edition of the activity has been held during the 2020-2021 academic year for 1st year students of Calculus at bachelor levels as well. Online meetings have also been the way to answering questions in a session devoted to it.

When it comes to numbers, for the first edition, a total amount of 158 students were enrolled. 50 curves of implicit functions were identified (cardioid, nephroid, lemniscata, cissoids, etc). The activity was developed by groups of up to 3 students, which represented nearly 99% of participation. Each group was given a curve from the pool randomly. Students were provided with a bonus point (1 out of 10) as a reward in case of adequate submission. The activity was set when the course had reached 75% of its regular path and represents an optional marking grade of 10% of the total. For the second edition, the reward system changed. The submission allowed substituting the lower grade obtained during the course. 20 groups (58 students) submitted adequate projects, which represents 50% of participation. The activity was set when the course had reached 75% of its regular path and represents a maximum yet optional marking grade of 10% of the total as well. It is interesting to point out that in the second edition, students were not locked down and lectures were held in Campus whereas for the former, students were locked down and lectures were fully remote.

Moreover, it is important to pinpoint that the Calculus course of first year has 6 European Credit Transfer System (ECTS) with an approximate amount of 4 hours of lectures per week during the whole academic year.

During the development of the activity the students i) plotted the curve in the canvas, ii) found the differentiation of an implicit curve (using chain rule and other concepts) and iii) used the derivative function for drawing a tangent line whose angle of rotation must be in accordance to the coordinates generated by the mouse pointer $(x,y)=(mouseX, mouseY)$. Maths and interactive programming were successfully blended together as a learning activity.

Fig. 2 shows an example of a Lemniscata and its tangent developed by one of the participants. A simple plot of the function in a 2D space is presented. Axes are drawn using lines and triangles and the function is plotted using points. The tangent line appears only when the mouse pointer is set on the curve at any point. A text indicating the slope is added for verification purposes.

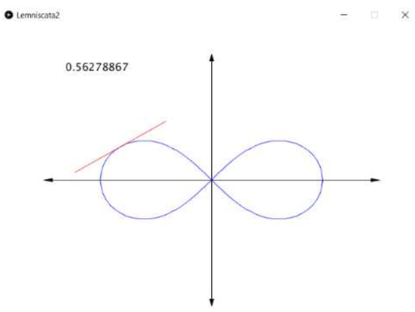

Fig. 2. Typical results obtained with a curve and its tangent line in Processing

The second part of the cornerstone projects is related to computational geometry. In order to explore adequate scope and limitations of the activity in a regular course, the workshop has been under development and preparation with more advanced students. These students had no prior knowledge in algorithmic programming but are acquainted to Calculus and coding.

The main idea is to expose students to computational geometry in a virtual space that is eventually compatible with BIM. Points are there treated in (x,y,z) text form and transformed to points instances of the "Rhino.Geometry" set of classes available in Grasshopper [19]. Rhino.Geometry wraps a set of methods that are applicable to several geometrical instances such as 3D points, lines, planes, surfaces and volumes using Python scripting. The result is a geometric language in which the designer develops complex geometries mathematically. Table 2 displays the present structure of the lessons.

Table 2. Structure of the lessons for the cornerstone project. Computational Geometry

Points, lines, planes, surfaces, volumes	Draw functions Draw derivatives Draw tangent planes using gradient vectors	GH and Python. List, tuples, dictionaries
Grasshopper	**Functions in GH**	**Coding**

Fig. 3 shows a typical window of an algorithmic programming snippet. One can see boxes and links between those boxes, which are conceived for treating certain types of input and for generating certain types of output. These boxes can be also tailor-made using Python, Visual Basic or C# languages, which opens a vast array of possibilities for manifold applications in engineering.

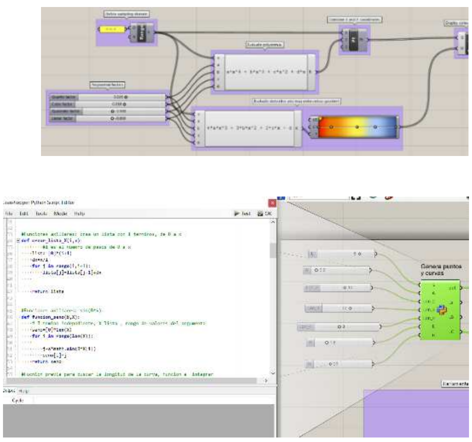

Fig. 3. Schematics of visual algorithmic programming including connections and codes.

The result of these codes is visualized in Rhino as shown in Fig.4. Students can develop geometries (from simple to complex) using mathematics, visual programming and beautiful visualizations.

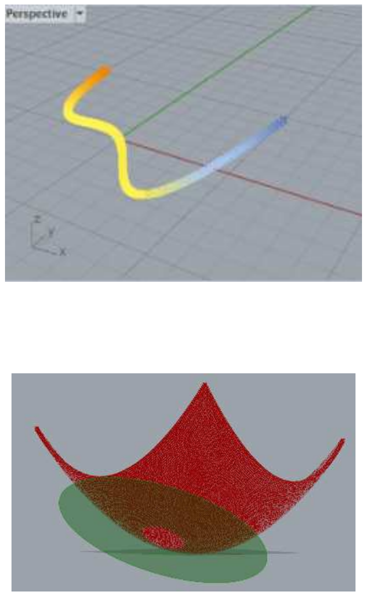

Fig. 4. Simple geometries developed in virtual spaces using computational geometry. Curves and surfaces.

IV. (S)(T)(E)(A)(M) WORKSHOPS

The core of the project is a set of workshops aimed at providing Contruction 4.0 concepts using a (S)(T)(E) approach. Smart Infrastructure, Digital Fabrication, BIM and Extended Realities represent Construction 4.0 branches that are covered with the set of activities. Some of the workshops have been systematically developed in the context of Master courses while others are prepared for future deployment.

A. Sensor-to-cloud

Knowledge on basic electronics and circuitries is a must in all engineering branches. Low-cost prototyping platforms are ideal tools for massive educational deployments in which hands-on activities are developed. In the last years, workshops on the use of sensors, data acquisition systems and user interfaces have been developed at the School in the form of lessons for introductory electronics using the platform Arduino [20]. Electronic prototyping platforms include a range of electronics such as programmable boards, sensors, mechanical parts, simple open-source software that can be afforded by the laboratory facilities (both technically and economically). A vast amount of online content and resources for students is nowadays available. The platform is considerably used by DIYers and STEAM-based educational programs. Object-oriented, event-driven interactive applications in a diversity of realms can be developed. The language syntax is identical to Processing, one of the platforms used for the cornerstone projects. On the other hand, an IoT platform developed at our School for connecting sensors to the cloud is used for the corresponding cloud services. Table 3 displays the structure of the required lessons.

Table 3. Structure of the lessons for Sensor-to-cloud

LEDs Knobs	Analog (LDR, Accel) Digital (Laser, Ultraound)	Servomotor
Basic circuitry	**Sensors**	**Actuators**
Data types Functions	Measurement accuracy Rotation	Concepts on things, keys, tokens, payload
Coding	**Calibration**	**Cloud services**

A basic structure of an Arduino code follows two functions: i) setup(), in which aspects such as initialization of functions, serial communication or other fixed parameters are established. This function executes once and must contain not invariable parameters. Subsequently, ii) loop() which runs indefinitely. It runs according to the order of written commands from top to bottom and repeats in a loop. The speed of execution between each loop can be regulated by using the delay command. We can see then than students acquainted with the cornerstone project follow a sort of continuation of tasks using same syntaxes.

In previous editions of the workshop the students i) connect basic circuitry of sensors and servomotors, understand the basics of microcontrollers and ii) send the measured magnitudes to the cloud via the provided IoT platform. Fig. 5 shows images of some of the already developed workshops and Maker experiences.

Fig. 5. Sensor-to-cloud developed in recent years in which sensors, microcontrollers and interfaces are ut together.

B. Maths-to-3D print

Knowledge on basic concepts of 3D printing is a must in all engineering branches. Students are increasingly acquainted with 3D modelling, which is a major requirement for generating physical objects using 3D printing. However, not all students have been adequately exposed to the generation of physical objects. The main aim of this workshop is to link concepts of computational geometry treated in the cornerstone project to the materialization of mathematically defined surfaces and volumes. Students are guided in the generation of a complex shape with specific requirements for 3D printing (reduced volume, reduced thickness, need of support material, etc). The workshop is straightforward for students acquainted with the Rhino.Geometry namespace depicted in the cornerstone project. At the end of the workshop, students 3D print out a complex shape (like the one displayed in Figure 6 whose mathematical definition is entirely known and defined by the students. 3D printers as well as base material are provided by the School in limited amounts. Students are also briefed with economy and sustainability conditions for avoiding unnecessary generation of pieces. Figure 6 displays the virtual shape, the Python snippet within the Grasshopper environment and the physical shape.

Table 4. Structure of the lessons for maths-to-3D print

Surfaces, BRep, Volume	Thickness, density, need of support, total volume, printing time	STL, IGES
Computational geometry	**3D printing requirements**	**File formats**

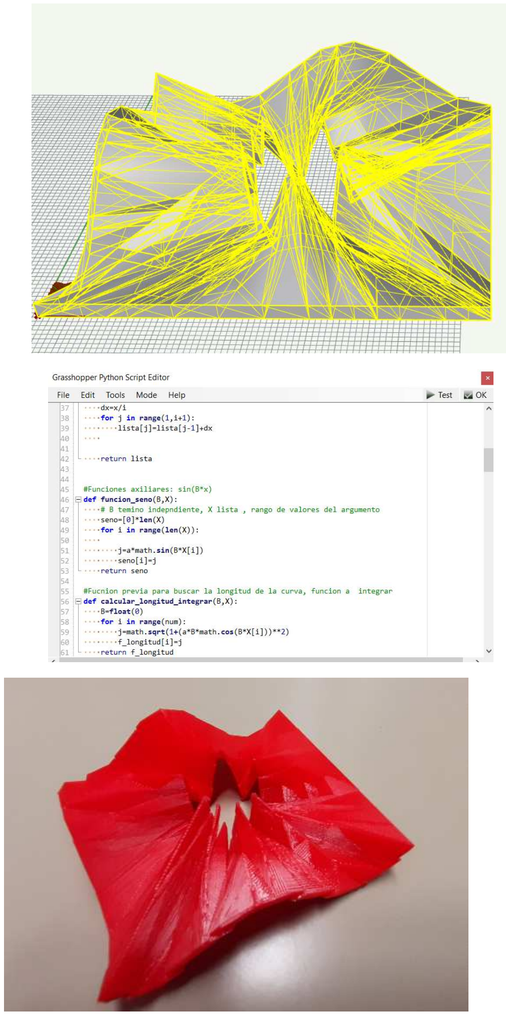

Fig. 6. Maths to print. Virtual and Physical geometries of a complex surface and its corresponding programming in Python.

C. Scan-to-BIM

Knowledge on basic concepts of BIM is also a must in AEC. Students are, however, unevenly acquainted with 3D modelling using specialized Software that is increasingly interoperable and user-friendly such as Revit [22], which also includes computational geometry tools such as Dynamo [23]. Basic BIM tutorials and courses have been available in the AEC educational sector for several years. Reviews on educational practices, needs and challenges of BIM in AEC classrooms are available [24]. 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. BIM-friendly environments are crucial for interoperability and as result, they represent an ideal standard in education at various levels. All sorts of 3D branches such as modelling, measurement, simulation, monitoring, construction tracking, and computational geometry can seamlessly communicate one to another. Proper ontologies and protocols need to be established for such purposes.

This particular workshop is not related to basic tutorial of a given BIM platform. Instead, it is conceived as a continuation of the computational and mathematical geometry set developed in previous workshops. Scan-to-BIM is a workshop in which students use a Terrestrial Laser Scanner developed at the School for the generation of point clouds in simple geometries such as planes, surfaces or volumes. Point clouds are measured and sent to algorithmic programming tools in BIM-enabled platforms such as Grasshopper or Dynamo. The analysis of the measurement requires mathematical understanding and identification of methods for the definition of these geometries in a virtual space in which these geometries can be embedded (S)(E)(M). This workshop is aimed at introducing students to the “as-built” concept. The build environment is increasingly virtualized at design levels using BIM but also, increasingly virtualized at construction stages using several technologies, in which Terrestrial Laser Scanners are often used.

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. However, it is emerging as a new teaching tool, capable of generating a new environment several sources of information are concentrated in a 3D virtual model. Students can be physically present during the generation of the point cloud 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. TLS emerges as one of the natural devices to bring real 3D information from the site to civil engineering classrooms. As an alternative, a DIY laser scanner was developed at the School (Fig. 7) and facilitates its use in AEC classrooms.

Fig. 7. Terrestrial Laser Scanner developed at the School (Virtual and Physical)

The workshop begins with measurement in live sessions. The TLS measurement process is presented as well as the workflow to obtain 3D point clouds in real time using a BIM-enabled Terrestrial Laser Scanner. This device sends to Grasshopper (the computational geometry platform) filtered points in real time already in the Rhino.Geometry namespace format, which facilitates the workshop to the students who get directly the point cloud. This previous step is also aimed at triggering cognition by means of an immersive visualization of 3D point collection and thus, understanding of the active principles behind professional TLS can be illustrated. A scientific critical debate of the accuracy of the results can be triggered in the classroom together with factors that affect the measurement such as the environmental light, the reflectivity of the material, the angle of incidence of the laser beam on the object surface, positioning errors or range limitations. Figure 8 displays the measurement set deployed in the last edition in which a surface, a sphere and a wall were used as examples.

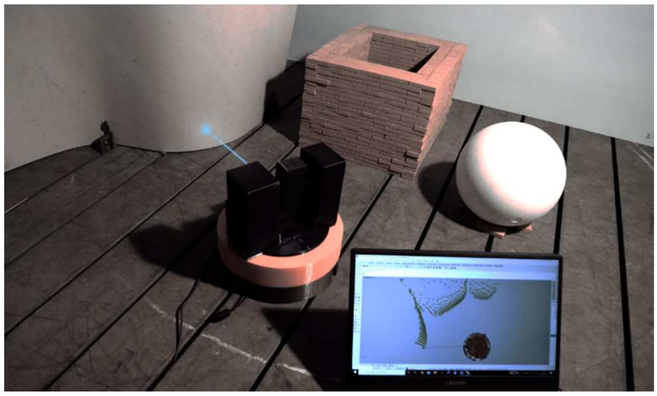

Fig. 8. Measurement set, Scan-to-BIM of a sphere, wall and surface.

Results are then embedded in Grasshopper and the workshop consists of identification of simple geometries such as planes, surfaces and volumes. Figure 9 shows examples of the results obtained with the TLS already visualized using the Rhino.Geometry namespace. Further explanations about the development and functionalities of the TLS have been submitted for publication in a journal paper.

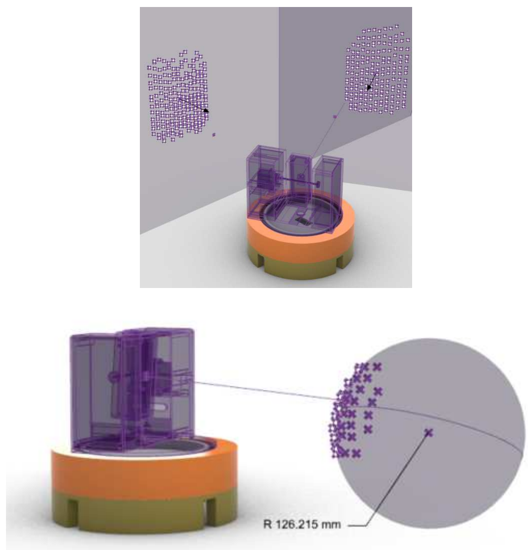

Fig. 9. Phyical measurement of the set within Grasshopper.

D. More than meets the eye. Extended realities

This workshop is nowadays under development. VR and AR technologies are relatively well-established tools with a diversity of applications spanning many fields. VR is an interactive simulated environment generated with computers which replaces the user's physical world with a fully synthetic environment. The interaction between such an environment and the user is typically generated with special screens, soundsystems, and joysticks embedded in customized helmets or glasses. AR is a real-world environment enriched with layers of information that are perceived by the user by means of multiple modalities. Screen-infused glasses with embedded hardware are one typical application of AR systems. However, mobile phones, light projectors or other reality-enhancers are also considered as such. In such scenarios, the user's awareness of the real environment is preserved by compositing physical/ virtual worlds in a blended space. The user sees the real environment and layers of graphical information (or text) that is added and updated in real time. One of the uncontested contributions of VR/AR is their potential to enhance sensorial perception as well as to trigger advanced learning to users by means of immersive experience because realistic immersive creations represent tools for visual communication of massive data. So far, the workshop has been related to the development of VR and AR applications that enhance the perception of the structural behavior of real tests [25] using sensors, microcontrollers, the cloud and a VR user interface. The results obtained are very promising for limited users in research facilities but it is less affordable and accessible for larger groups. A thorough understanding of the technologies available nowadays is needed for the sake of deploying meaningful activities related to extended realities to larger groups in AEC classrooms.

Fig. 10. Virtual reality reproduction of a test using real time measurements.

V. CAPSTONE PROJECTS. DIGITAL TWINS AND ROBOTICS

The development of digital twins from scratch by students represents an ideal capstone project in which all technologies are summarized [26]. Physical systems that may or not included automation and robotics are virtualized using sensors. Computational geometry and/or visual programming tools allow developing graphical user interfaces for twinning the assets. Applications with minimum ingredients for basic examples can be developed in due time by civil engineering students that have followed the personal learning path. The systematic use of DT proves useful and affordable for the development of encompassing capstone projects. Interestingly, the development of digital twins provides a basic understanding of cyber-physical systems, which is one of the main branches that can be found in Construction 4.0. Digital Twins have already been explored by many students at our laboratory facilities and guidance for cornerstone projects has already been provided. Figure 11 to 13 show several examples already developed in structural analysis, steel structures or geotechnics.

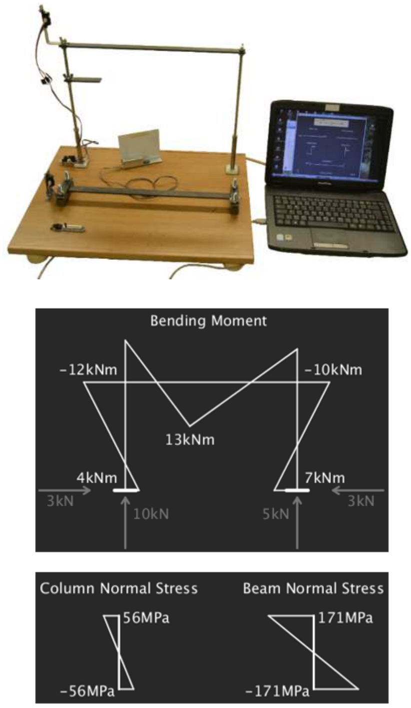

Fig. 11. Digital twin of a miniature one-bay frame

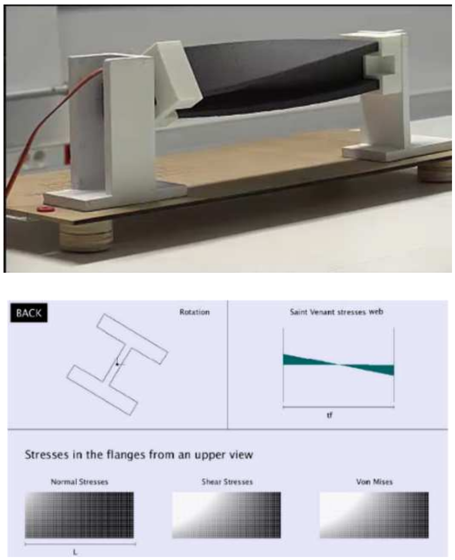

Fig. 12. Digital twin of a miniature beam subjected to torsion loads

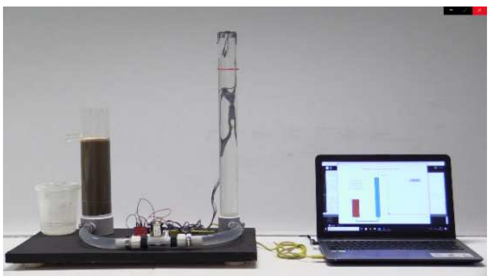

Fig. 13. Digital twin of a miniature reproduction of a pereability test in geotechnics

VI. Conclusive remarks

In this paper, a set of cornerstone, capstone and intermediate workshops encompassing fabrication, coding and instrumentation in civil engineering courses are presented. The set is aimed at facilitating a personal learning path on Construction 4.0 to AEC students. The workshops are conceived in a way added technical competences are added to motivation and creativity among students by merging (S)(T)(E)(A)(M) concepts. Blending together these concepts is becoming paramount in civil engineering schools since the present generation of civil engineering students encounter massive advances in sensing, information and computing technologies that continuously provide to the Architecture, Engineering and Construction sector (AEC) ways for dealing with the large variety of technical information at all project stages.

The implementation of these developments in the classroom in the context of Construction 4.0 is under development. The effectiveness of these tools has been assessed in some workshops (Cornerstone projects in Calculus, with positive results) but have not yet fully deployed in others (i.e., more than meets the eye).

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 crucial 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. The paper shows an example of a cyber-physical system that can be infused within AEC classrooms with scientific (S), technological (T), engineering (E), artistic (A) and mathematical (M) perspectives.

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References

[1] F. Leite, Y. Cho, A. Behzadan, S. Lee, S. Choe, Y. Fang, Y. R. Akhavian, and S. Hwang. "Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry". Journal of Computing in Civil Engineering, vol. 30(6), 2016.

[2] W. Boles, J. Wang. "Construction Automation and Robotics in Civil Engineering Education Programs". Journal of Professional Issues in Engineering Education and Practice, vol. 122(1), pp. 12-16. 1996

[3] S. Christodoulou. "Educating Civil Engineering Professionals of Tomorrow." Journal of Professional Issues in Engineering Education and Practice, vol. 130(2), pp. 90–94. 2004

[4] L. Feisel and A. Rosa. "The Role of the Laboratory in Undergraduate Engineering Education." Journal of Engineering Education, vol. 94(1), pp. 121–130. 2005

[5] J. Pearce. "Building research equipment with free, open-source hardware." Science, vol. 337(6100), pp. 1303–1304, 2012.

[6] F. Bouquet, J. Bobroff, M. Fuchs-Gallezot, and L. Maurines. "Project-based physics labs using low-cost open-source hardware". American Journal of Physics, vol. 85, pp. 216-222, 2017.

[7] A. Alavi, P. Jiao, W. Buttlar and N. Lajnef. "Internet of Things-enabled smart cities: State-of-the-art and future trends". Measurement, vol. 129, pp- 598-606. 2018

[8] M. Karami, G. McMorrow and L. Wang. "Continous monitoring of indoor environmental quality using an Arduino-based data acquisition system". Journal of Building Engineering, vol. 16, pp. 412-419. 2018

[9] J. Paul and W. Buytaert. "Chapter One: Citizen Science and Low-Cost Sensors dor Integrated Water Resources Management". Advances in Chemical Pollution, Environmental Management and Protection, vol. 3, pp. 1-33. 2018

[10] C. Basto, L. Pelà and R. Chacón. "Open-source digital technologies for low-cost monitoring of historical constructions". Journal of Cultural Heritage, vol. 25, pp. 31-40. 2017.

[11] R. Chacón, D. Codony, and A. Toledo, "From physical to digital in structural engineering classrooms using digital fabrication". Computer Applications in Engineering Education, vol. 25, pp. 927–937, 2017.

[12] J. Huang, S.K. Ong and A. Nee. "An approach for augmented learning on finite element analysis". Computer Applications in Engineering Education, vol. 27 (4). 2019

[13] R. Chacón and S. Oller. "Designing experiments using digital fabrication in structural dynamics". Journal of Professional Issues in Engineering Education and Practice, vol. 143, pp. 1–9, 2016.

[14] R. Slocum, R. Adams, K. Buker, D. Hurwitz, H. Mason, C. Parrish and M. Scott. "Response spectrum devices for active learning in earthquake engineering education." HardwareX, 4, e00032. 2018

[15] K. Kensek. "Integration of Environmental Sensors with BIM: case studies using Arduino, Dynamo, and the Revit API." Informes de la Construcción, vol. 66(536), e044, 2014.

[16] R. Chacón, H. Posada, A. Toledo and M. Gouveia. "Development of IoT applications in civil engineering classrooms using mobile devices". Computer Applications in Engineering Education, vol. 25, pp. 927–937, 2017.

[17] A. Sawney, M. Riley, J. Irrizarri. "Construction 4.0 An Innovation Platform for the Built Environment". London: Routledge. 2020

[18] Pogosyan, M. (2020). "Development of individual learning paths system in engineering education". Frontiers in Education 2020.

[19] http://processing.org

[20] Grasshopper. Algorithmic modelling for Rhino. https://www.grasshopper3d.com/

[21] http://arduino.cc

[22] Revit. Multidisciplinary BIM Software. Autodesk. https://www.autodesk.com/

[23] Dynamo. Open source graphical programming for design. https://dynamobim.org/

[24] Wang, L., Huang, M., Zhang, X., Jin, R., Yang, T. 2020a. "Review of BIM Adoption in the Higher Education of AEC Disciplines". Journal of Civil Engineering Education, 146(3). https://doi.org/10.1061/(ASCE)EI.2643-9115.0000018.

[25] Gürdür Broo, D., Boman, U., Törngren, M., 2021. "Cyber-physical systems research and education in 2030: Scenarios and strategies". Journal of Industrial Information Integration, 21. https://doi.org/10.1016/j.jii.2020.100192.