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DIGITAL TWINS IN CIVIL AND ENVIRONMENTAL ENGINEERING CLASSROOMS

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Abstract. Digital twins are understood as digital replica of physical models whose behavior can be observed simultaneously (digitally and physically) in real time. These tools are increasingly used in advanced industries for several purposes. The digital representation provides both the elements and the dynamics of how an Internet of Things (IoT) device operates and lives throughout its life cycle. Despite its complexity, the materialization of these digital artifacts in their simplest form imply the use of a threefold technology: sensors, data acquisition systems (DAS) and graphical user interfaces (GUI). This paper describes several educational exploratory tasks performed at the School of Civil Engineering in Barcelona (UPC) aimed at developing meaningful yet simple digital twins for civil engineering classrooms. The project encompasses the use of simple GUIs that show in real time physical systems from several disciplines such as structural engineering, soils mechanics, hydraulics, environmental engineering, coastal engineering or structural dynamics. The project has shown potential for civil engineering classrooms at two levels: i) these portable tools can be used pedagogically for demonstrating key concepts with a high degree of interactivity, ii) the development of these artifacts (from sensors to GUIs) may provide a key understanding of several concepts associated with IoT mechanics for civil engineering students. It is noteworthy that nowadays, average students are seldom acquainted with sensors, electronics and virtualization of physical magnitudes at Bachelor and Master level. IoT technologies will be needed in civil engineering classrooms in the following years due to the increasing trends related to automation, monitoring and digitalization that the construction industry will undertake. Experimental and numerical pedagogical activities may be enriched with this concept since they allow navigating from physical to virtual realms and vice versa. The paper includes several examples with real applications as well as some recommendations for its potential application.

1 INTRODUCTION

One of the greatest challenges in civil engineering education in the years to come is to provide an adequate perspective to students at Bachelor and Master levels when it comes to all changes the professional sector will experience. Digital technologies disrupt industries as can be testified by the photography and the musical sectors, just to cite a few. The relentless trend of sophistication in automation, sensor deployment and control in construction is providing a huge potential for IoT applications in the sector [1]. The mechanics of automation and the use of sensors have been largely investigated for robotic construction and massive deployment of sensors [2][3] but their systematic application in civil engineering schools as part of the curricula is still in its infancy [4].

One the other hand, students are increasingly acquainted with the vast array of possibilities that are provided by digital technologies. The use and development of Software is natural for them in all subjects and fields. *Programming*, *CAD* or *Simulation* applications erect a vast framework of tools that are routinely used in civil engineering classrooms at various levels [5] [6] [7]. Laboratory activities are also one of the greatest experiences that students gather during their higher education journey [8] [9] [10].

Moreover, the educational sector has been increasingly infused with a vast array of pedagogical tools that make adequate use of both physical and digital realms separately. Project-based learning PBL [11], constructivist hands-on experiences [12], learning through making [13] or massive open online courses [14] are only a fraction of new educational experiences that are enriching civil engineering classrooms. However, few educational frameworks related to the blend of both physical and digital realms within civil engineering subjects are available [15] [16].

This paper presents some efforts undertaken at the School of Civil Engineering at UPC, Barcelona, Spain aimed at blending digital technologies and physical civil engineering problems by means of the concept of digital twin. The effort has been performed by educators from several core disciplines of civil engineering such as structural engineering, geotechnical engineering, coastal engineering, environmental engineering and hydraulic engineering.

Several examples have been built from scratch by students with varying level of achievement and success. The main idea for all cases has been to analyze the potential use of digital twins from a twofold perspective:

- As portable artifacts to be brought to the classrooms for illustration and demonstration of particular phenomena.
- As potential tools to be developed by students as a PBL, constructivist way of encompassing theory, fabrication, programming and physical-to-digital connection by means of electronics.

The project has been under development during the 2017-2018 academic year. Some of the findings are pinpointed as well as some recommendations related to the methodology that may be implemented in civil engineering classrooms.

2 DESCRIPTION OF THE PROJECT

The School of Civil Engineering has facilitated the development of an academic project aimed at studying the potential of digital twins as a pedagogical vehicle for civil engineering classrooms. The project belongs to the series of "Ajuts de millora a la docència" or AMD grants (Learning enhancement scholarships) in which students develop weekly tasks intended to improve teaching within the school. In the AMD grants given to the group in the 2017-2018 edition, these tasks are provided and supervised by educators within four different fields:

- Steel Structures Design
- Geotechnical engineering
- Coastal Engineering
- Environmental Engineering

The origin of the project can be found in similar experiences developed in the educational space "Camins Makers" at the School in other subjects:

- Structural Dynamics (2015-2016, 2016-2017, 2017-2018)
- Hydraulics (2016-2017)

In past editions of the yearly AMD grants, students have been developing a vast array of artifacts for civil engineering purposes. The use of 3D printing, open-source hardware and software as well as fabrication has provided an interesting learning environment in which lectures, workshops and educational research are performed and constantly evolving. Different tools such as electronic prototyping boards and computers (Arduino, Raspberry Pi), 3D printers, Web-based or desktop-based graphical user interfaces (GUI) and physical tools are brought together with a constructivist approach. Students involved in these lectures, workshops or grants can use the space quite freely as well as the available tools with the help of technicians. The space has limited access to these students so far.

Digital twins are understood as digital replica of physical models whose behavior can be observed simultaneously (digitally and physically) in real time. The digital representation provides both the elements and the dynamics of how an Internet of Things (IoT) device operates and lives throughout its life cycle. Despite its complexity at various levels (scale reduction, multi-physics, multivariable, sensor embedness or other issues), the materialization of these digital artifacts in their simplest form imply the use of a threefold technology

- Sensors
- Data acquisition systems (DAS)
- Graphical user interfaces (GUI)

The educational experience was deployed with the aim of understanding several features of the concept "Digital Twin" from an educational perspective. The aforementioned twofold perspective (portable artifacts for the classroom or project to be developed by students) has been under scrutiny at various levels:

- Individual projects undertaken by AMD students with a weekly work load of five hours during three months (either Bachelor or Master Levels).
- Collective projects undertaken by Master students in the form of simple digital twins that have been developed within the frame of the course Structural Dynamics.

The development of such projects require hands-on activities: Physically, the construction of artifacts whose level of complexity may vary depending on the field. Digitally, the development and coding of Software. The physical-to-digital conversion (or ADC in electronic jargon) is provided by sensors and microcontrollers. Civil engineering students are often acquainted with fabrication and programming but not necessarily with electronics. One of the greatest challenges of the projects is to assess the latter lack of background. In either case, a set of common tools/resources were provided and established as standard equipment:

- A civil engineering problem with routine application in lectures.
- Open-source, low-cost hardware (sensors and microcontrollers).
- Open programming software platforms.

3 TOOLS

The Arduino platform [17] and Processing [18] have been systematically used as the Hardware-Software combination for the development of the educational experience due to their availability at the school, their open-source nature of both and their increasing popularity worldwide. A brief description of both tools is addressed succinctly.

3.1 The Arduino platform

Arduino is an open hardware-prototyping platform. A set of up to 6 analog and 13 digital pins are available in this board. Connection to computers is performed via USB (for uploading programs or providing power). Any program following the Arduino syntax can be uploaded/modified as needed within the Arduino IDE (or alternatively, from other platforms). The board can be programmed to sense the environment by receiving analog inputs from many sensors, and/or to affect its surroundings by controlling lights, motors, and other actuators or digital devices. Add-in peripheral bluetooth shields can be added easily (other more sophisticated boards have BT capabilities embedded) as well as other modules for connectivity such as WiFi module, Xbee protocols or similar. A more powerful tool (Arduino DUE) provides a superior performance. The typical structure of Arduino programs is fairly simple can be divided in three main parts: structure, values (variables and constants), and functions. These functions require at least two parts, or blocks of statements. The setup() function is called when a sketch starts. It is used to initialize variables, pin modes, start using libraries, define communication protocols etc. The setup function will only run once, after each power up or reset of the Arduino board. After creating a setup() function, the loop() function which is repeated consecutively. Programming with the Arduino environment provides capabilities related to the Serial Port Communication and/or to the BT connections if needed. Analog signals from sensors and microcontrollers can be sent to the computer or to BT receivers.

3.2 Processing

Processing is a visual language and development environment built on top of the Java programming language. It allows generating computer simulations and visual graphics from scratch. In this context, Processing is used for developing graphical user interfaces. Processing follows a syntaxes that is very similar to the one used in the Arduino IDE. This may facilitate the structure of the project to students that need to learn from scratch both syntaxes. The platform allows developing object-oriented programs. Classes depict the behaviour of objects. Processing includes widely depicted in-built classes defining the behaviour of vectors or images (PVector, PImage). In addition, the Serial port connection is fairly straightforward and results measured by sensors can be derived to Processing in real time with a great ease.

3.3 Fabrication

Physical or digital fabrication tools (such as 3D printers, laser cutting or classical tools) have been used in the development of the project. The construction of the physical counterparts represents a very important aspect of the twin, in which creativity and constructivism is present all the time.

4 EXAMPLES

The project has been under development during the 2017-2018 academic year. For some examples, only preliminary results can be included in this document due to submission constraints. In the following, digital twins related to several fields are described. For all cases, the structure of the artifact follow a similar pattern which is illustrated in figure 1.

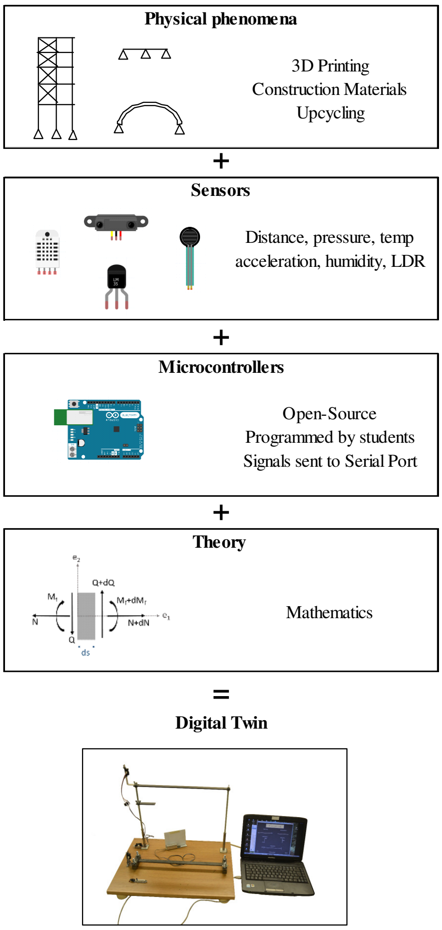

Fig. 1 The pattern in all digital twins

4.1 Steel structures

Digital twins in the design of steel structures have been built for various purposes. As an example, basic digital twins aimed at showing both physically and digitally the planar behavior of steel frames subjected to both vertical and horizontal loads. Pressure and distance sensors controlled by the user provide data in real time that is visualized in the form of typical bending or shear force diagrams and stresses distributions, that follow adequate mathematical formulations. Figure 2 shows an example of the physical artifact as well as its digital twin. A scale-reduced frame provided with sensors and microcontrollers is used as a portable example for teaching. In this case, the frame is built for several load directions at variable positions (vertical, horizontal)

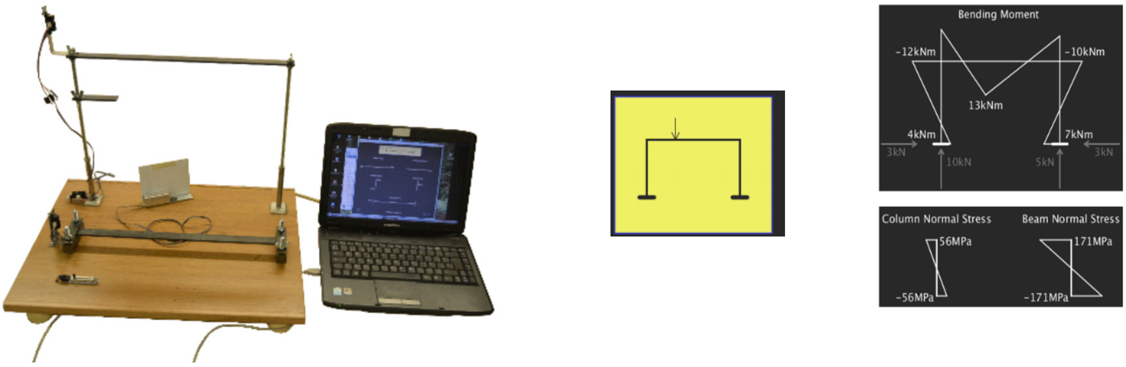

Figure 2. Digital twins in steel structures. Physical models and real time applications for the case of vertical load applied on the beam

4.2 Geotechnical Engineering

Digital twins in geotechnical engineering have been initially built for the reproduction of the permeability test in sands and lines. This test requires the design of a soil column through which water passes during a certain amount of time. After percolating, the liquid is stored in a tank, whose height is measured with distance sensors and subsequently shown in real time digitally. The supporting structures have been designed with impervious 3D printed materials. Figure 3 shows schematics of the designed twin.

Figure 3. Digital twins in geotechnical engineering. Schematics, 3D printed impervious, sensors and microcontrollers.

4.3 Coastal Engineering

Digital twins in coastal engineering have been initially conceived for the reproduction of a wave maker. This construction requires the design of a channel in which waves are generated cyclically by means of a servomotor. The height of the waves is measured in real time and visualized digitally. Creative forms for visualizing waves in real time can be obtained in Processing by using object-oriented programming. Figure 4 shows a conceptual design of the wave generator. It has been found that the construction of a portable object is quite complex.

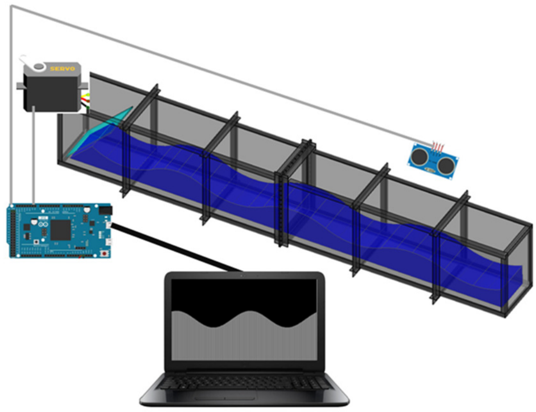

Figure 4. Digital twins in coastal engineering. Schematics, sensors, microcontrollers and real time applications

4.4 Environmental Engineering

Digital twins in environmental engineering were initially built up for the monitoring of a microbial fuel cell. The microcontroller monitors the voltage decrease during the oxidation of organic matter in wastewater treatment systems. The process lasts several hours. Visual applications must account for this fact in order to present results in a menaningful way. Physical and digital objects can be seen in figure 5.

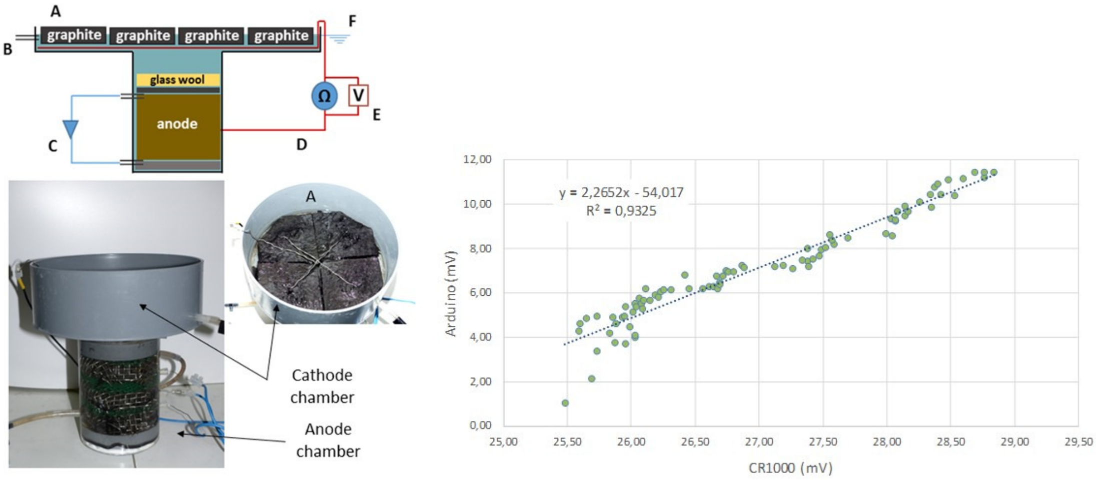

Figure 5. Digital twins in environmental engineering. Schematics and measurements comparisons (Arduino vs. traditional dataloggers).

4.5 Hydraulics

Digital twins in hydraulics have been built for the reproduction of an existing hydraulic channel. The channel is provided with sensors (distance) that generate data related to the water flow and its speed. With these results, real-time, object-oriented particles systems are developed in Processing. As a result, one can see in real time how particles are accelerated similarly to the flow (figure 6). This digital twin is not portable but allows showing simple graphical user interfaces to students during laboratory experiences.

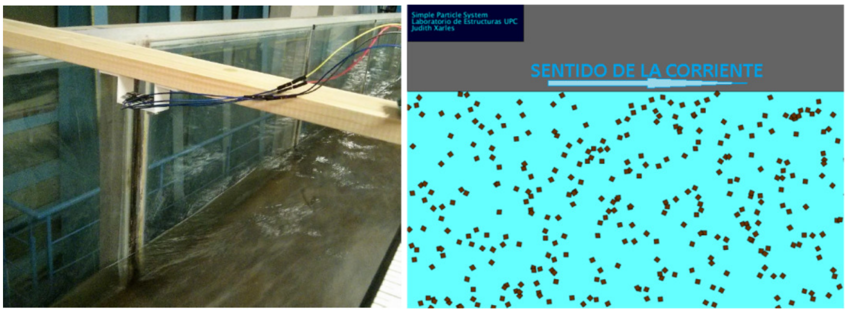

Figure 6. Digital twins in hydraulics. Channel, sensors and digital applications

4 PRELIMINARY RESULTS AND FINDINGS

The on-going project digital twins consists of a constructivist hands-on set of examples built by students in which interfaces between data coming from sensors are visually displayed by applications developed by them. In this visualization, these simple yet meaningful artifacts including sensors, microcontrollers and development are encompassed to the classical needs associated with civil engineering problems. For the twofold perspective that is discussed throughout the paper (portable objects and hands-on PBL project), preliminary results related to the experience show that digital twins can be a very useful tool for the understanding of physical phenomena in their portable or in the laboratory forms. Their use as a PBL project for civil engineering students has not yet been fully assessed though. Questions related to the needed educational methodology for the application of such methodology need to be addressed and applied in the classroom in order to provide a vaster educational insight.

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