ACTA IMEKO
ISSN: 2221-870X
December 2022, Volume 11, Number 4, 1 - 8

Digital twins based on augmented reality of measurement instruments for the implementation of a cyber-physical system

Annalisa Liccardo[1], Francesco Bonavolontà[1], Rosario Schiano Lo Moriello[2], Francesco Lamonaca[3], Luca De Vito[4], Antonio Gloria[2], Enzo Caputo[2], Giorgio de Alteriis[2]

[1] *Dipartimento di Ingegneria Elettrica Università di Napoli Federico II Naples, Italy*
[2] *Dipartimento di Ingegneria Industriale Università di Napoli Federico II Naples, Italy*
[3] *Dipartimento di Ingegneria Informatica, Modellistica, Elettronica e Sistemistica, Università della Calabria, Italy*
[4] *Dipartimento di Ingegneria, Università degli Studi del Sannio, Italy*

ABSTRACT
The recent increase on the Internet of Things and Industry 4.0 fields has led the research topics to investigate on the innovative technologies that could support these emerging topics in different area of applications. In particular, the current trends are to close the gap between the physical and digital worlds, thus originating the so-called Cyber-Physical System (CPS). A relevant feature of the CPS is the digital twin, i.e., a digital replica of a process/product with which user can interact to operate on the real world. In this paper, the authors propose an innovative approach exploiting an Augmented Reality solution as Digital Twin for the measurement instrument to obtain a tight connection between the measurements as physical world and the Internet of Things as digital applications. In fact, by means of the adoption of the 3D scanning strategy, Augmented Reality software and with the development of a suitable connection between the instrument and the digital world, a Cyber-Physical System has been realized as an IoT platform that collect and control the real measurement instrument and makes its available in Augmented Reality. An application example involving a digital storage oscilloscope is finally presented to highlight the efficacy of the proposed approach.

Section: RESEARCH PAPER

Keywords: Cyber-physical systems; digital twin; remote control; augmented reality; measurement instrumentation

Citation: Annalisa Liccardo, Francesco Bonavolontà, Rosario Schiano Lo Moriello, Francesco Lamonaca, Luca De Vito, Antonio Gloria, Enzo Caputo, Giorgio de Alteriis, Digital twins based on augmented reality of measurement instruments for the implementation of a cyber-physical system, Acta IMEKO, vol. 11, no. 4, article 15, December 2022, identifier: IMEKO-ACTA-11 (2022)-04-15

Section Editor: Leonardo Iannucci, Politecnico di Torino, Italy

Received November 14, 2022; **In final form** November 26, 2022; **Published** December 2022

Corresponding author: Rosario Schiano Lo Moriello, e-mail: rschiano@unina.it

1. INTRODUCTION

The concept of Cyber-Physical Systems (CPS) was first presented in 2006, introduced by Helen Gill of the National Science Foundation [1], in the United States, to denote a plane of "local sensation and manipulation of the physical world" correlated with a virtual plane of "real-time control and observability." The concept is presented as an evolution of embedded systems in which the computational capability and its effects descend deep into every physical component of the system and even within the materials [2].

From this initial vision, the concept of CPS has taken on a breadth over time that does not facilitate its unambiguous and definitive conceptualization or representation. The most common definition of CPS, as integration of computational resources and physical processes, now seems too simplifying as other elements, particularly large-scale network connectivity, have rightfully entered the perimeter of CPS.

In its current most common definition, CPS is considered as an integration of systems of different natures whose main purpose is the control of a physical process and, through feedback, its adaptation in real-time to new operating conditions. This is achieved by the fusion of physical objects and processes, computational platforms, and telecommunications networks [3], [4].

The term physical refers to actual objects as they are "perceivable" by human senses, while the term cyber refers to the virtual image in which actual objects are represented and enriched with one or more additional layers of information. The relationship between physical objects and their virtual "interpretation" has been referred to by some authors as the effective term "social network of objects" [5].

CPSs, therefore, are based on related objects that, through sensors, actuators, and network connections, generate and acquire data of various kinds, thus reducing distances and information asymmetries between all elements of the system [6].

With the help of widespread sensors, the CPS can autonomously determine its current operational state within its environment and the distance between its component objects. Actuators perform planned actions and execute corrective decisions, optimizing a process or solving a problem [7].

Decisions are made by intelligence that evaluates information internal to the CPS and, in some scenarios, also information from other CPSs [8]-[10].

In this context, a very important aspect is the interaction with measurement systems (in terms of both sensors or sensor networks and actual measurement instruments). In this case, the aim is to make the measurement system an integral and priority part of the CPS; realizing the digital twin of measurement systems allows possible users to be able to "touch with their hands" is, therefore, a desirable condition [11].

Remote control of instruments is a research activity that saw its first examples in the 1990s; however, such activities were only aimed at enabling measurements to be made by remote programming of instruments. Instead, the point of view, both educational and industrial, has changed, requiring a faithful replication of the system to be controlled with direct interaction of the operator (whether student or worker) on the instrument.

For this reason, the authors propose an augmented reality-based approach to create a digital twin of the measuring instrument that can be controlled and operated remotely; for this purpose, several enabling technologies inherent in Industry 4.0 and Internet of Things paradigms are used, such as augmented reality and MQTT communication protocols. The goal is to enable users to operate the remote instruments as if they were in their presence [12].

The paper is organized as follows: in Section 2, a literature review on CPS and AR-based applications is presented, while the proposed method is described in detail in Section 3. An application example is given in Section 4 before drawing the conclusions in Section 5.

2. RELATED WORK

Providing for an exhaustive review of the exploitation of AR in cyber-physical systems is a difficult challenge due to the wide variety of configurations and application fields they are interested in, such as in additive manufacturing [13]-[16] , industry 4.0 [17]-[22] and autonomous vehicle [23]-[25]. As an example, an application of CPS in the manufacturing environment is proposed in [7], where the real-time data are sent into cyberspace through different types of networks to build a digital twin of the machine tool. Finally, AR is exploited as an interface between human and the CPS to mainly retrieve information about the on-going processes.

In [26], the authors present a closed-loop cooperative human CPS for the mining industry that exploits the information obtained from AR and Virtual Reality (VR) systems. The main goal of this research is to allow human interaction with the mining operation by means of a deep integration of AR and VR; this integration makes visual information available to the operator that is supported during the operations in terms of making the correct decisions, conduct inspections and interacts with the equipment.

A compelling CPS for autonomous vehicle applications has been proposed in [9]. The authors have developed an AR indoor environment for testing and debugging autonomous vehicles that act in such a way to realize dynamic missions in laboratory environments for planned mission testing and validation; the proposed solution is realized by exploiting ground and aerial systems, motion cameras, ground projectors, and network communications to obtain a standard procedure for testing and prototyping environment for CPSs. Finally, in a field test performance of perception, planning, and learning algorithms in real-time have been evaluated.

Furthermore, in [27], context-aware guidance of cyber-physical process has been proposed for the press line maintenance process. In particular, by means of a suitable context graph, it was possible to manage and structure the CPS sensor data. In addition, an AR application is adopted to support the interaction of users with the CPS processes thanks to the integration of position and marker sensors in the proposed solution; the object detection is improved by means of the digital data that ensures improved guidance in the process execution. The adoption of AR with CPS allows to support the end-user in the manual tasks where it is guided and monitored during the operations.

An interesting application is evaluated in [28], where a suitable AR navigation system for industrial applications has been proposed. The authors have developed a prototype of an autonomous vehicle that interacts with a robot arm. In particular, the robot arm interacts with the vehicle when the correct position is reached, and the vehicle navigation is obtained by exploiting an AR solution based on markers recognition; these markers are used as system reference position points.

Finally, the research carried out in [29] has highlighted that the integration of IoT platforms and AR software as Digital Twin is the most suitable technology to close the gap between the physical and digital worlds by means of the definition of a Digital Twin architecture model, the introduction of a Digital Twin service and the investigation on the key elements of Industry 4.0 required for the realization of a Digital Twin.

Differently from the solutions mentioned so far and mainly intended to exploit AR as a fundamental information layer for the interaction with CPS, the authors want to propose a method to realize a CPS for measurement instruments that act as an interface between the actual and AR world. Instrument control and the related measurements are not carried out as simulations, but the AR interaction between user and rendered instruments corresponds to real physical state changes in the real world. To accomplish the considered target, a general framework for the definition, implementation, and assessment of an example of Digital Twin application will be presented in the following by referring to a typical measuring instrument.

3. PROPOSED METHOD

The method adopted to create a digital twin of the measurement instrument exploits an augmented reality approach based on the framework shown in Figure 1. The first step is dedicated to generating the 3D geometric model of the desired instrument; operating approaches typical of reverse engineering can be applied to the purpose. In particular, the reverse

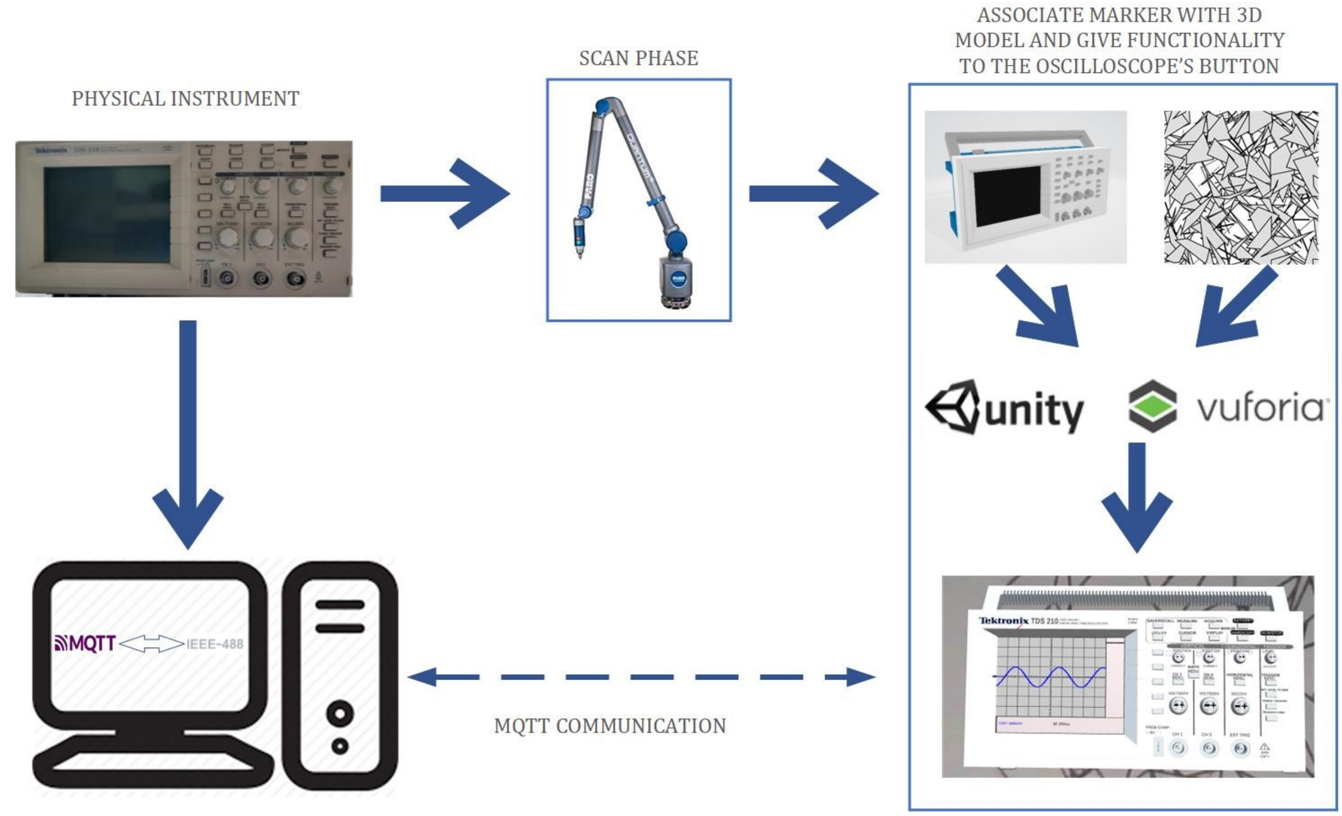


Figure 1. Proposed solution workflow: from the physical world to the digital twin.

Figure 2. 3D scanning strategy of the instrument exploiting a non-contact Laser ScanArm by FARO™.

engineering approach uses (*i*) suitable tools to acquire 3D spatial data of objects and (*ii*) dedicated software environments to manipulate and convert them into useful information. FARO's non-contact Laser ScanArm [30] (Figure 2) was chosen to acquire the image and the main dimensional information about the instruments; the output of the scan operation consists of clouds of points in the 3D space. Thanks to Computer-Aided Design (CAD) systems, it has been possible to define mathematical representations allowing the reconstruction of the instrument geometry, thus obtaining a 3D CAD model of the desired object. In order to move from point clouds to the extraction of both surface and geometrical characteristics, suitable software as well as reverse engineering techniques were combined to provide a very efficient and robust solution. In particular, the point clouds were first handled using Geomagic Wrap software [31] to transform those data into polygonal meshes, and then the 3D image reconstruction was performed. From the reconstruction of case, front panel, back panel and support systems, the 3D model of the instrument has been obtained; buttons and knobs have been separately reconstructed and placed one by one in their well-defined positions. The scanning phase produces a file with an OBJ extension containing an empty container, a simple 3D view of the instrument (Figure 3).

The successive step aimed at transforming the obtained 3D object into an augmented interactive object; the 3D graphics development platform Unity has been used to the purpose. Every interaction that the user performs on the augmented reality object is translated in the corresponding operation executed on the actual instrument. To this aim, a typical IoT protocol called Message Queue Telemetry Transport (MQTT) [32] is used to communicate with the laboratory where the instruments are placed. In particular, the lab is equipped with a

Figure 3. Oscilloscope 3D model obtained from the 3D scanning strategy.

personal computer connected from one side to Ethernet network and on the other side to the instruments. The PC converts received MQTT messages into messages compliant with the protocol used by instruments (IEEE488), in order to forward to the instruments commands and request corresponding to AR user's operations. A suitable software on the PC implements a MQTT client, which has the role of receiving all messages from the augmented instrument and sending them to the actual instrument and vice versa. Communication among different MQTT clients is assured by a third entity, the so-called broker, mandated to dispatch messages to the client subscribed to specific information arguments, referred to as Topic [33]. To assure reliable operations and continuous service as well as maintain a complete control on the exchanged data, it was decided to exploit a private broker.

To realize an augmented reality application, Unity exploits a software development plug-in, namely Vuforia, allows to recognize images chosen as a target. In particular, Vuforia is capable of assessing the quality of image target and thus providing feedback regarding the possible usage or not of that image as a target. Images with a more complex pattern proved to be the best candidate as a target in terms of 3D reconstruction location and stability; for this purpose, the one adopted for the realised application is shown in Figure 4 and produced a satisfying evaluation from the Vuforia tool.

In an augmented reality application, the image target has an important role, since it allows to locate a 3D object in a scene; when an AR application starts and the camera mounted on the device frame the considered image target, digital replicas of the object, in this case the instruments are superimposed on the image itself.

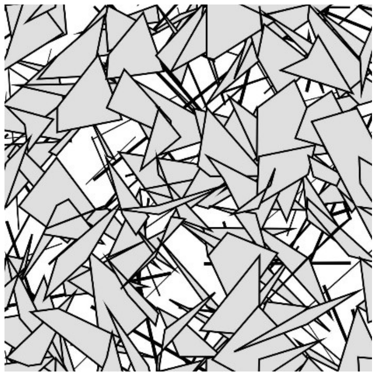
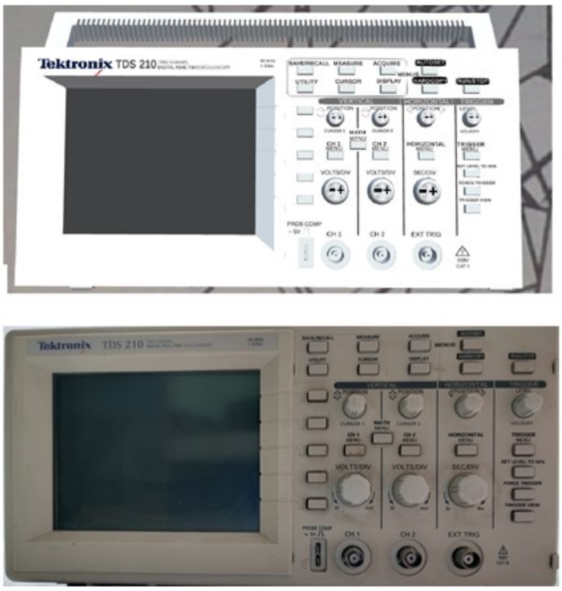


Figure 4. Example of image target exploited for rendering and spatially locating AR instruments.

As said before, the obj file contains a 3D replica of the instrument. Therefore, it was necessary to import the obj file into the Unity environment and make the appearance of this object similar to the actual one. Regarding the oscilloscope shown in Figure 3, it has been necessary to add the labels above each key, the model of the instrument in the top left-hand corner as well as additional markings and symbols that are present on the real instrument. In addition, compared to the real instrument, two '+' and '-' symbols were added on each knob to allow the user to rotate them with step values similar to those of the actual instrument.

The result of this operation is shown in Figure 5.

The final step regards the communication between AR and actual instrument; to this aim, a software module in C# language has been implemented to recognize button pressure on the virtual object and perform the corresponding operation by sending the command to the actual instrumentation (Figure 6). As said before, the protocol used to communicate with the real instrumentation is MQTT, so an MQTT client was created within the application running on the user device (e.g. smartphone, tablet or smart glasses) to send commands to the actual instrumentation and to receive the corresponding responses from them if necessary, as in case of the so-called queries [34]. In particular, the developed C# module can



a.

b.

Figure 5. Comparison between the actual instruments and its digital twin; instrument view in the AR software environment (a), actual instrument (b).

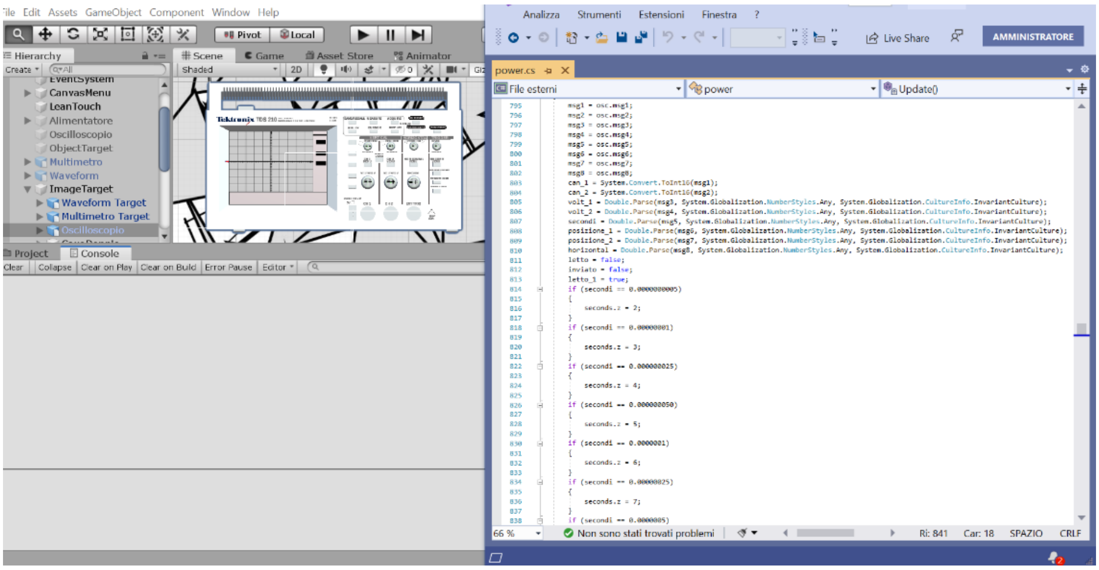


Figure 6. Example of implemented C# module for interaction between user, AR reconstruction and actual instrumentation.

recognize if the sequence of button pressed, and consequently of operations, are correct and in this case, sends the command to the real instrument; as previously said, in the laboratory is present a PC with a suitable software that receives these messages and sends them to the associated instruments. If the command requires a response from the instrumentation, the C# module reads these responses that are properly managed to be shown on the display of the 3D AR instrument. In this way, the user has the feeling of interfacing with the actual instrument even if he is in a different location.

Finally, to make the instrument's behaviour as close as possible to reality, secondary effects such as pressure emulation, knob movement or button backlighting are also reproduced.

4. APPLICATION EXAMPLE OF THE IMPLEMENTED AR-BASED CYBER-PHYSICAL SYSTEM

This section aims to present a case study of the proposed approach by considering the typical operations that student have to perform on the digital oscilloscope during basic metrology courses. To this aim, a proper mobile application has been realized to assess the reliability of the method.

When the student interacts with the rendered 3D instrument, the first operation he/she must perform, as with the actual instrument, is to switch it on. In fact, when the oscilloscope power button is pressed in the AR application, a query is sent to the actual instrument to retrieve the waveforms currently present on the instrument's display as well as its configuration parameters (as an example, horizontal, s/div, and vertical, V/div, resolution, Figure 7).

This way, the student can gain awareness and knowledge about the signal currently acquired and displayed on the actual oscilloscope and, consequently, change the parameters, depending on the operations to be performed, by acting on the corresponding knobs of the V/div and s/div.

In addition, the student can have information about the signal coupling. As on the actual instrument, the “CH1 MENU” button must be clicked on, and the information appears on the right-hand side of the display (Figure 8). In the example case shown in the Figure 8 the waveform coupling is “DC”.

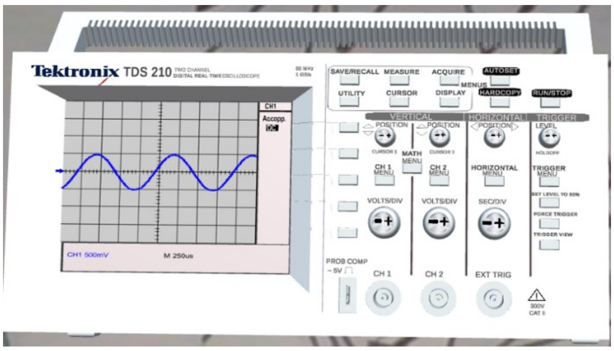


Figure 8. CH1 Menu Selection on the AR instrument.

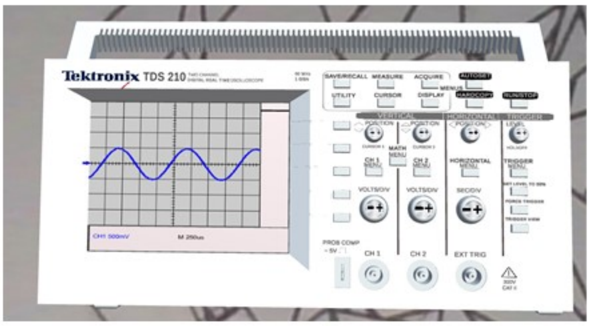


Figure 7. Waveform and resolution information on the AR display after turning on.

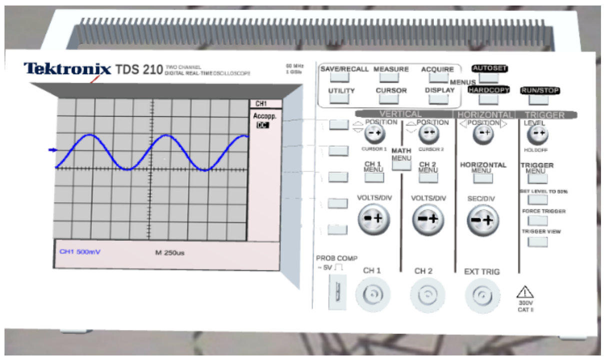
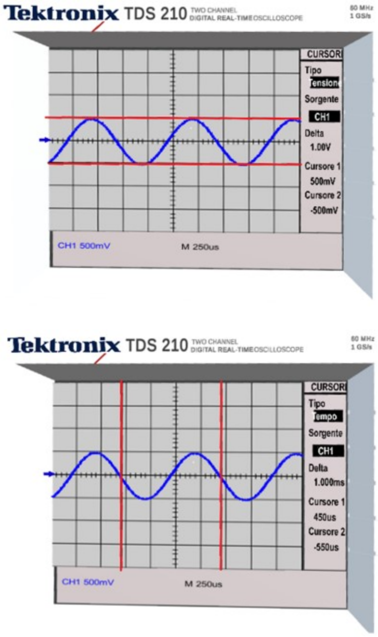


Figure 9. Signal level.



a)

b)

Figure 10. Evaluation of a) peak-peak amplitude and b) period of the signal.

By turning the specific knobs located on the “CH1 MENU” button it is possible to change the signal level (Figure 9), so that the signal is moved up or down according to the axis origin. This is important if the student has both signals on the instrument display and he doesn’t want to display them as superimposed.

Moreover, it is possible to change the trigger level as well as on the actual instrument and perform operations with the cursors to measure period and amplitude of the signal. Figure 10.a shows how the cursors were used to evaluate the peak-to-peak amplitude of the signal, while in Figure 10.b the period was measured. It is worth noting the relevant concurrence between the display of the instrument rendered within the AR application and that characterizing the actual instrument in the laboratory.

As a further case study, a typical students’ exercise is presented, mandated to measure the variation in amplitude and phase of the output signal referred to an RC filter circuit; in particular, an RC filter with a cut-off frequency of 1.7 kHz was used. Figure 11 shows the measurement setup present in the actual laboratory, where in this case the device under test (DUT) stands for the RC filter.

As can appreciated in the Figure 11, the input signal of the filter is connected to channel 1 of the oscilloscope while channel 2 will show the output signal of the filter; Figure 12 shows the corresponding results as the frequency of the input signal rises. In particular, Figure 12.a presents the acquired (and almost superimposed) waveforms of the two channels when an input sine wave with a frequency equal to 200 Hz has been applied. When the frequency of the generated signal increases up to 1 kHz, (Figure 12.b), the output waveform begins to be attenuated and delayed with respect to the input one. As the frequency is increased to 5 kHz (Figure 12.c), the filter effect of the considered DUT proves to be evident with a significant attenuation and displacement of the output waveform.

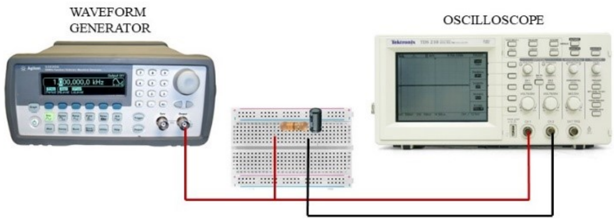
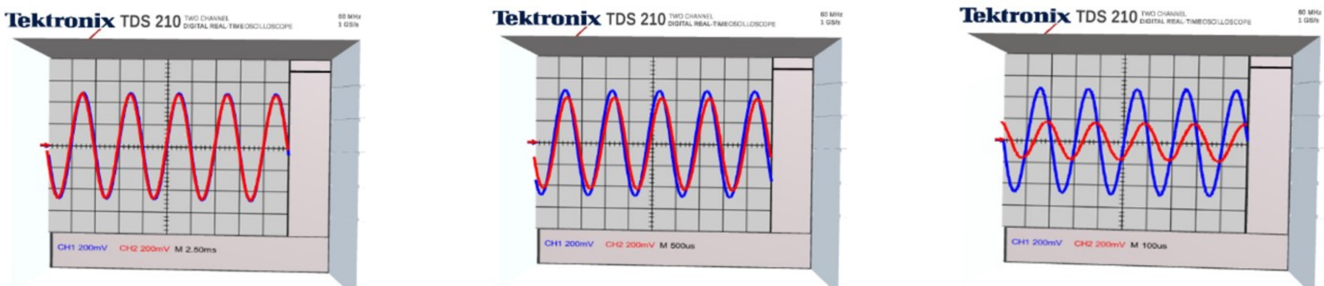


Figure 11. Laboratory setup in experiments with RC Filter.

As for the actual lab experience, gain and phase shift of the filter can be measured by means of cursors as in Figure 10; for the sake of the brevity, the procedure is not shown in the paper.

5. CONCLUSIONS

The purpose of the current research study was to evaluate the capabilities of CPS in the measurement framework. In particular, a suitable method to develop a Digital Twin has been proposed, and a real implementation referred to an oscilloscope has been presented. In fact, starting from a 3D scanning strategy, the actual instrument is reconstructed in Augmented Reality, each front panel element is associated with an instruction of the actual instrument, and then an AR application is developed by means of the Vuforia and Unity environments. Moreover, a suitable communication, based on the MQTT protocol, is adopted between the actual instrument and its 3D reconstruction. To this aim, a personal computer is exploited to realize *(i)* the physical connection with the actual instrument, *(ii)* the internet or local connection with the MQTT client, and *(iii)* an interpreter for the command sent to the instrument and the responses from the instrument outputs to the AR application. As an example, a typical application is evaluated where a filtered signal has been correctly displayed and measured in terms of frequency in the AR application. So, it was proved that the oscilloscope could be used in an AR framework where it is remotely controlled and sent the actual measure (acquired in the physical world) to the Augmented Reality world. It has been demonstrated that a CPS for the measuring instruments can be realized, highlighting that instrument as Digital Twin acts in the same way as those in the real world.



a) b) c)

Figure 12. Evolution of signal output of RC filter: a) signal frequency input equal to 200 Hz, b) signal frequency input equal to 1 kHz, c) signal frequency input equal to 5 kHz.

REFERENCES

[1] R. Bahati, H. Gill, Cyber-physical Systems. The Impact of Control Technology, Open J. Soc. Sci. Sci. Res. Publ, vol. 5, pp. 161–166, 2011.

[2] M. Bashendy, A. Tantawy, A. Erradi, Intrusion Response Systems for Cyber-Physical Systems: A Comprehensive Survey, Comput Secur, p. 102984, 2022. DOI: 10.1016/j.cose.2022.102984

[3] S. Zanero, Cyber-physical systems, Computer (Long Beach Calif), vol. 50, no. 4, pp. 14–16, 2017. DOI: 10.1109/MC.2017.105

[4] W. Wolf, Cyber-physical systems, Computer (Long Beach Calif), vol. 42, no. 03, pp. 88–89, 2009.

[5] F. Cicirelli, A. Guerrieri, G. Spezzano, A. Vinci, Edge computing and social internet of things for large-scale smart environments development, IEEE Internet Things J, vol. 5, no. 4, pp. 2557–2571, 2017. DOI: 10.1109/JIOT.2017.2775739

[6] M. Prist, A. Monteriù, E. Pallotta, P. Cicconi, A. Freddi, F. Giuggioloni, E. Caizer, C. Verdini, S. Longhi, Cyber-physical manufacturing systems: An architecture for sensor integration, production line simulation and cloud services, Acta IMEKO, vol. 9, 2020, no. 4, pp. 39–52. DOI: 10.21014/acta_imeko.v9i4.731

[7] F. Hu, Cyber-physical systems. Taylor & Francis Group LLC, 2014.

[8] J. Shi, J. Wan, H. Yan, H. Suo, A survey of cyber-physical systems, Int. conference on wireless communications and signal processing (WCSP), Nanjing, China, 9-11 November 2011, pp. 1–6. DOI: 10.1109/WCSP.2011.6096958

[9] B. Scherer, Hardware-in-the-loop test based non-intrusive diagnostics of cyber-physical systems using microcontroller debug ports, Acta IMEKO, vol. 7, 2018, no. 1, pp. 27–35. DOI: 10.21014/acta_imeko.v7i1.513

[10] P. S. Matharu, A. A. Ghadge, Y. Almubarak, Y. Tadesse, Jelly-Z: Twisted and coiled polymer muscle actuated jellyfish robot for environmental monitoring, Acta IMEKO, vol. 11, 2022, no. 3, pp. 1-7. DOI: 10.21014/acta_imeko.v11i3.1255

[11] F. Gabellone, Digital Twin: a new perspective for cultural heritage management and fruition, Acta IMEKO, vol. 11, 2022, no. 1, 7 pp. DOI: 10.21014/acta_imeko.v11i1.1085

[12] M. Y. Serebryakov, I. S. Moiseev, Current Trends in the Development of Cyber-physical Interfaces Linking Virtual Reality and Physical System, Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), Saint Petersburg, Russian Federation, 25-28 January 2022, pp. 419–424. DOI: 10.1109/ElConRus54750.2022.9755545

[13] H. Lhachemi, A. Malik, R. Shorten, Augmented reality, cyber-physical systems, and feedback control for additive manufacturing: A review, IEEE Access, vol. 7, 2019, pp. 50119–50135. DOI: 10.1109/ACCESS.2019.2907287

[14] A. T. Silvestri, V. Bottino, E. Caputo, F. Bonavolontà, R. Schiano Lo Moriello, A. Squillace, D. Accardo, Innovative Fusion Strategy for MEMS Redundant-IMU Exploiting Custom 3D Components, IEEE 9th Int. Workshop on Metrology for AeroSpace (MetroAeroSpace), 2022, pp. 644–648. DOI: 10.1109/MetroAeroSpace54187.2022.9856222

[15] A. T. Silvestri, M. Perini, P. Bosetti, A. Squillace, Exploring Potentialities of Direct Laser Deposition: Thin-Walled Structures, Key Engineering Materials, vol. 926, 2022, pp. 206–212. DOI: 10.4028/p-82vyug

[16] A. T. Silvestri, I. Papa, F. Rubino, A. Squillace, On the Critical Technological Issues of CFF: Enhancing the Bearing Strength, Materials and Manufacturing Processes, 2021. DOI: 10.1080/10426914.2021.1954195

[17] Y. Lu, Cyber physical system (CPS)-based industry 4.0: A survey, Journal of Industrial Integration and Management, vol. 2, 2017, no. 03, p. 1750014. DOI: 10.1142/S2424862217500142

[18] B. Dafflon, N. Moalla, Y. Ouzrout, The challenges, approaches, and used techniques of CPS for manufacturing in Industry 4.0: a literature review, The International Journal of Advanced Manufacturing Technology, vol. 113, 2021, no. 7, pp. 2395–2412. DOI: 10.1007/s00170-020-06572-4

[19] G. de Alteriis, V. Bottino, C. Conte, G. Rufino, R. S. lo Moriello, Accurate Attitude Inizialization Procedure based on MEMS IMU and Magnetometer Integration, IEEE 8th Int. Workshop on Metrology for AeroSpace (MetroAeroSpace), 2021, pp. 1–6. DOI: 10.1109/MetroAeroSpace51421.2021.9511679

[20] S. Surdo, A. Zunino, A. Diaspro, M. Duocastella, Acoustically shaped laser: A machining tool for Industry 4.0, Acta IMEKO, 2020, vol. 9, 2020, no. 4, p. 60-66. DOI: 10.21014/acta_imeko.v9i4.740

[21] G. Mariniello, T. Pastore, A. Bilotta, D. Asprone, E. Cosenza, Seismic pre-dimensioning of irregular concrete frame structures: Mathematical formulation and implementation of a learn-heuristic algorithm, Journal of Building Engineering, vol. 46, 2022, DOI: 10.1016/j.jobe.2021.103733

[22] G. Mariniello, T. Pastore, D. Asprone, E. Cosenza, Layout-aware Extreme Learning Machine to Detect Tendon Malfunctions in Prestressed Concrete Bridges using Stress Data, Autom Constr, vol. 132, 2021. DOI: 10.1016/j.autcon.2021.103976

[23] G. Raja, S. Senthilkumar, S. Ganesan, R. Edhayachandran, G. Vijayaraghavan, A. K. Bashir, AV-CPS: Audio Visual Cognitive Processing System for Critical Intervention in Autonomous Vehicles, IEEE Int. Conference on Communications Workshops (ICC Workshops), 2021, pp. 1–6. DOI: 10.1109/ICCWorkshops50388.2021.9473647

[24] J. Wang, Z. Cai, J. Yu, Achieving Personalized k-Anonymity-Based Content Privacy for Autonomous Vehicles in CPS, IEEE Trans Industr Inform, vol. 16, 2020, no. 6, pp. 4242–4251. DOI: 10.1109/TII.2019.2950057

[25] C. Conte, G. de Alteriis, G. Rufino, D. Accardo, An innovative process-based mission management system for unmanned vehicles, IEEE Int. Workshop on Metrology for AeroSpace, MetroAeroSpace 2020, pp. 377–381. DOI: 10.1109/MetroAeroSpace48742.2020.9160121

[26] J. Xie, S. Liu, X. Wang, Framework for a closed-loop cooperative human Cyber-Physical System for the mining industry driven by VR and AR: MHCPS, Comput Ind Eng, vol. 168, 2022, p. 108050. DOI:

[27] K. Kammerer, R. Pryss, K. Sommer, M. Reichert, Towards context-aware process guidance in cyber-physical systems with augmented reality, 4th Int. workshop on requirements engineering for self-adaptive, collaborative, and cyber physical systems (RESACS), 2018, pp. 44–51. DOI:

[28] T. I. Erdei, Z. Molnár, N. C. Obinna, G. Husi, A novel design of an augmented reality based navigation system & its industrial applications, Acta IMEKO, vol. 7, 2018, no. 1, pp. 57–62. DOI: 10.21014/acta_imeko.v7i1.528

[29] S. Aheleroff, X. Xu, R. Y. Zhong, Y. Lu, Digital twin as a service (DTaaS) in industry 4.0: an architecture reference model, Advanced Engineering Informatics, vol. 47, 2021, p. 101225. DOI: 10.1016/j.aei.2020.101225

[30] FARO, Technical Specification Sheet. Online [Accessed 28 November 2022] https://it-knowledge.faro.com/Hardware/FaroArm_and_ScanArm/FaroArm_and_ScanArm/Technical_Specification_Sheet_for_the_Edge_FaroArm_and_ScanArm

[31] Artec3D, Geometric Wrap. Online [Accessed 28 November 2022] https://www.artec3d.com/3d-software/geomagic-wrap?utm_source=google&utm_medium=cpc&utm_campaign=12554714117&utm_term=geomagic%20wrap%7C%7Ckwd-524408837989&utm_content=119631253619%7C%7C&keywor

d=geomagic%20wrap&gclid=Cj0KCQiAmaibBhCAARIsAKUlaKS3tal5eCZFfdElgEh
[32] ISO/IEC 20922:2016 Information technology – Message Queuing Telemetry Transport (MQTT) v3.1.1," 2016. Online [Accessed 28 November 2022] https://www.iso.org/standard/69466.html
[33] OASIS, MQTT version 3.1.1, 2015. Online [Accessed 28 November 2022] http://docs.oasis-open.org/mqtt/mqtt/v3.1.1/
[34] SCPI Consortium, Standard commands for programmable instruments (SCPI), volume 1: Syntax and style, USA, May 1999. Online [Accessed 28 November 2022] https://www.ivifoundation.org/docs/scpi-99.pdf