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Digital Twins-Based Self-Regulation System for Instrumentation Networks in IoT Applications

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Abstract: *The novel concept of Digital Twins has become ubiquitous in manufacturing operations. It allows the creation of a virtual environment, in which all devices (or even the system itself) have digital pairs (twins) at the cloud. Doing so, one can instantiate these digital pairs in order to perform predictions, for example. Moreover, the real and digital twins can communicate, exchanging information. In this context, this work studies the application of Digital Twins at instrumentation networks, in the context of Internet of Things (IoT). We propose a self-regulation system composed by sensor, microcontroller and Wi-Fi radio, connected to the ThingSpeak IoT platform. A low-cost real experiment was conducted, implementing the proposed digital twins-based self-regulation system, where a temperature signal is smoothed with a median filter aggregation scheme. The case study performed showed the feasibility of the proposed digital twins-based scheme applied to instrumentation systems for IoT scenarios.*

Keywords: *Digital Twins, Instrumentation, Self-regulation, IoT.*

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I. INTRODUCTION

Instrumentation is an area of great importance in science, turning possible to obtain and analyze data from a given activity in real time for insertion (or not) of some type of control. For data collection, sensors are used, which make up the so-called Wireless Sensor Networks (WSNs), used with the objective of monitoring areas of interest.

In this context, a WSN is responsible for collecting data, processing it, and transmitting it through one or more sources, to a base station, which can act as a gateway to the Internet [11]. In Internet of Things (IoT) environments, there is a need to continuously collect data, generated by a heterogeneous set of sensors and objects ("things"), thus making this information available remotely to several user applications [18]. In this way, WSNs can be seen as the communication infrastructures of the IoT.

One of the challenges related to the use of multiple sensors in an IoT context concerns the analysis of the data to be transmitted. In this data analysis process, fusion and compression techniques are usually used, which discard irrelevant (or redundant) data, analyze patterns from historical series, in addition to determining characteristics and correlations, in order to generate quick and appropriate responses to the physical phenomena monitored.

Given this context, this work aims to investigate the application of Digital Twins [9] in IoT environments. It allows one to implement new techniques for acquiring, processing and communicating data from an instrumentation network. Here, we define an instrumentation network as a system composed by sensors, microcontroller, radio interface, and the cloud (Internet).

We propose a self-regulation scheme, based on the digital twins concept. In this framework, each physical sensor has its digital pair at the cloud. They exchange information; i.e., the physical sensor sends measurements collected from the environment to its digital twin, placed at the cloud. The latter uses received data to perform analysis; for example, if the received data have large variations or are noisy, this could mean that the physical sensor is out of calibration or has a bias. Thus, the digital sensor can send a message to their physical twin asking it to smooth the measured signal. This cycle closes a loop, implementing a self-regulation scheme.

In this work, the proposed self-regulation approach is implemented in a real scenario, and a case study is used to evaluate the proposal. An initial low-cost experiment was carried out using sensors, microcontroller and Wi-Fi communication to the cloud, in which temperature and humidity signals were smoothed through a median filter, showing the feasibility of the proposed system.

The rest of this work is structure as follows: Section II presents some fundamental concepts: the Internet of Things and the digital twins. The literature review is presented in Section III, clustering the applications of the digital twins concept in industry, communications and IoT / Network / Protocols. The proposed system and the results from the case study are presented in Section IV. Finally, conclusions are discussed in Section V.

II. FUNDAMENTAL CONCEPTS

2.1 Internet of Things

Today, IoT has become a popular term to describe eironments in which Internet connectivity and computing power extend to a variety of objects, devices, sensors, and other everyday items; that is, the IoT implies an interplay between the real (physical) and digital (virtual) worlds, where physical entities have digital parts and virtual representation on the Internet. Thus, "things" become aware of the context and can feel, communicate, interact, exchange data, information and knowledge [18].

In IoT environments, there is a need to collect data continuously generated by a heterogeneous set of sensors and objects, as well as to make this information available remotely to different applications and users. Through the use of intelligent decision-making algorithms, based on the information collected, quick and appropriate responses to physical phenomena can be given. These intelligent algorithms can be used to discard irrelevant data, analyze patterns from historical data, determine semantic and static characteristics and correlations, as well as increase scalability and robustness in IoT environments [18].

This means that the IoT was born with the aim of integrating the physical world with the virtual world using the Internet as the mean to communicate and exchange information. In addition, in order to provide seamless communication and interaction between real-world objects anytime and anywhere, today's complex interoperability problems must be solved. Many applications related to IoT are being implemented, generating solutions in different domains and environments. The applications are varied, covering several areas such as health, transport, agriculture, energy, industry and tourism, which makes IoT an interdisciplinary subject [16].

The Internet of Things can be seen as a paradigm for the evolution of the Internet in the coming years, and it predicts that everyday objects will increasingly gain processing, communication and sensing capabilities. This vision makes room for these objects to be incorporated into computer networks and start to interact autonomously, promoting a broad integration of the physical and digital world [7]. Within this perspective, applications become capable of employing the IoT infrastructure to perform computation in a widely distributed way and even providing proactive human-machine interfaces.

In the IoT domain, simple data aggregation techniques (arithmetic averages, median, the search for maximums and minimums, among others) have been used to reduce data traffic in order to decrease the energy consumption of sensor nodes [17], [6]. However, the efficiency of data aggregation algorithms depends on the correlation between the data generated by the different sources of information [5]. The correlation can be spatial, when the values generated by nearby sensors are related; temporal, when sensor readings change slowly over time; or semantics, when information from different data packages can be classified under the same semantic group, such as data generated by sensors placed in the same room.

This aspect favors the elimination of redundancy (one of the goals of data aggregation techniques), but also ensures data accuracy. This is important, as this summarization of data can represent a loss in accuracy [2], which is a typical requirement for many applications of WSNs and instrumentation systems in general. Accuracy can be defined as the degree of proximity between the observed measurement and its actual value [12]. With an efficient correlation of the original data, it is possible to achieve a greater reduction in the amount of data for the same accuracy of the aggregated data.

2.2 Digital Twins

The concept of a digital twin was initially introduced by Michael Grieves in [9] in the industry, as a virtual replica of something being produced. The basic idea is to be able to compare the digital representation with the projected product in the physical world, in order to obtain a better understanding of what is being produced.

According to [10], the product development process (its life cycle) can be started in the virtual world, creating a prototype (or project) of a given product. In this way, tests can be carried out, formats evaluated, and a three-dimensional model of the product created, until a version that is considered adequate, according to its specifications, is reached. From there, the physical twin is created, from the proper validation of the virtual product. In addition, several instances of the digital twin can be created, allowing simulations and tests necessary for the proper validation of the product, thus reducing manufacturing costs.

One can think of other advantages and applications of using the concept of digital twins. For example, three-dimensional virtual replicas of machines can be used in employee training, preventing production from being stopped.

The information obtained by the physical twin, and transmitted to the virtual replica, can be used to feed instances in the digital world in order to perform tests or predictions about the physical product. On the other hand, the analyzes performed by the virtual instances can serve to improve the performance of the real product. Thinking about an instrumentation system, a digital twin of a given sensor can be instantiated in the virtual domain and the information obtained in this domain can be used to evaluate the quality of the measurements performed. If the real sensor is subject to noise or some measurement error, which is perceptible in the virtual world, an instance of the digital twin can be used to implement some systematic error reduction techniques [12], to be replicated by the real sensor. This allows the system to self-regulate through communication between the twins, which is, in turn, the proposal of this paper.

One way to implement the concepts of digital twins is from the communication infrastructure of the Internet of Things. In this sense, one can imagine that every device (or "thing") can have a replica in the virtual world; more specifically, in the "cloud". Therefore, IoT and cloud computing can be combined to provide communication between the twins.

Digital twins are also expected to form a network, a "Digital Twin Web", in the future. Digital Twin Web follows a similar structure to the World Wide Web and consists of meta-level digital twins that are described as digital twin description documents and distributed via Digital Twin Web servers. Standards must be established before the Digital Twin Web can be used efficiently, and having an easily accessible server implementation can foster the development of those standards. Twinbase is an open-source, Git-based Digital Twin Web server developed with user friendliness in mind. Twinbase stores digital twin documents in a Git repository, modifies them with Git workflows, and distributes them to users via a static web server, from which the documents can be accessed via a client library or a regular web browser. Twinbase is built with GitHub repository, Pages, and Actions, but can be extended to leverage other providers or self-hosting. Autiosalo et al. described the underlying architecture of Twinbase to support the creation of derivative and alternative server implementations [3]. The Digital Twin Web requires permanent, globally accessible, and transferable identifiers to function properly, and to address this issue, in [3], the concept of digital twin identifier registry was also introduced. Performance measurements showed that the median response times for fetching a digital twin document from Twinbase varied between 0.4 and 1.2 seconds depending on identifier registry.

In terms of communication, the concept of Data Link was first presented by Autiosalo et al. at the conceptual level [3]. However, Ala-Laurinaho et al. presented a way to implement the Data Link in practice and included a proof of concept for this implementation [1]. The idea of the Data Link is to provide a single access point to all data available on the physical entity. The paper proposes an API (Application Programming Interface) Gateway for linking the systems (or features) that form a digital twin. The API gateway simplifies the communication between these services by forwarding messages and taking care of authentication. Data Link provides information about the digital twin and its features via a user interface. The information is stored in a YAML document, the format which authors of [1] standardize to allow the implementation of Digital Twin Web (DTW). DTW is analogous to the document-based World Wide Web (WWW) but made for digital twins.

III. LITERATURE REVIEW

Most approaches on using Digital Twins focus to solve a particular problem (e.g., equipment health monitoring, product design, system design, quality evaluation). However, a unified DT framework to be used in multiple coordinated applications (scheduling/dispatching, rerouting, self-organization and optimization, etc.) is still needed. Qamsane et al. proposed a unified DT platform that operates within a Software-Defined Control (SDC) framework for flexible control reconfiguration of smart manufacturing systems [14]. The proposed DT platform uses historical and real-time data to provide the SDC controller with a centralized view that is used to provide comprehensive DT capabilities such as to predict and detect anomalies, monitor equipment health, monitor production in real-time, optimize scheduling/dispatching, improve the system self-organizing and learning, and propose novel control plans.

The advances of the Internet, Internet of Things (IoT), big data, cloud computing, and artificial intelligence (AI) brought valuable opportunities to many industries. In manufacturing, the big data involve a large volume of structured, semi-structured and unstructured data generated from the product lifecycle. The increasing digitalization of manufacturing is opening up opportunities for smart manufacturing. The manufacturing data are collected in real-time and automatically by IoT. Collecting and analyzing a large volume of manufacturing data to find laws and knowledge has become the key of smart manufacturing. Meanwhile, the digital twin breaks the barriers between the physical world and the cyber (physical) world of manufacturing. In [15] the concepts of big data and digital twin were reviewed. In addition, the data sources, data processing and data applications of big data in manufacturing are discussed, as well as the applications of digital twin in manufacturing. The similarities and differences between big data and digital twins in manufacturing are compared from different aspects, including the general and data perspectives, as well as their respective advantages are discussed. The complementarity of digital twins and big data is discussed. Moreover, how the digital twins, big data and services are joined up to promote smart manufacturing is illustrated in [15].

Work in [13] presents a concept of cloud Digital Twin for 5G networks aiming to perform continuous assessment, monitoring and proactive maintenance through the closed-loop data from physical entities to the virtual counterparts and vice-versa. Within the 5G DT, the digital 5G model is run alongside with the physical 5G network to perform operational predictions, and enforce optimized decision into the living network and associated services. A 5G DT architecture allows the virtual 5G DT to start with a simple form and then by employing AI mechanisms, it would evolve to become a more comprehensive model achieving better precision through the assistance of data updating. The DT technology allows for easy and cost-effective access to 5G with highly flexible and repeatable development approaches. It enables proactive modelling of data traffic and security risks for test/validation purpose, driving operational and energy efficiency, helping accelerate the research and time-to-market for new disruptive services.

The structure of the digital environment, presented in [8] as an element of the “digital twin” technology, allows for optimizing energy consumption in a complex technological system for the production of phosphorus from apatite-nepheline ore waste. The digital environment is based on computational intelligence methods, such as deep neural networks, which make it possible to conduct automated deep analysis for large volumes of technological data. A significant number of optimization parameters leads to a polyextremity of the response surface of the optimality criterion (total energy consumption by the technological system). Therefore, to ensure global optimization, simple enumeration of the criterion values at various parameter combinations was used. The contribution of the presented study ([8]) for the information support of chemical energy technological system (CETS) lies in the developed structure and software of the digital twin environment (DTE), which allows for optimizing CETS functioning according to energy and resource efficiency. The results of the numerical experiment demonstrate the capabilities of the created software and the efficiency of the proposed multistage optimization procedure.

Work in [4] introduced an approach for a modeling and simulation-based engineering methodology linking different engineering perspectives for a better handling of the complexity in the development process of complex technical systems. A central aspect is the consequent use of models at each stage of the system development. The paper distinguish between three different types of models: (1) The System Model, representing an information repository that provides all relevant data of the system’s specification including cross-connected data for requirements, behavior, structure, etc; (2) the Product Model, representing a product database that provides all physical detail information and part specifications of the realized product; and finally (3) the Simulation Model, representing the executable code to run specific simulations which includes the corresponding conceptual and executable model and data. A special focus of the paper of [4] is set to the Simulation Model, presenting a realization approach on basis of Experimentable Digital Twins in Virtual Testbeds. The latter are provided by a generic software framework with various interfaces for the integration of arbitrary simulation algorithms, while Experimentable Digital Twins manage the necessary simulation data and structures. Combining them to a comprehensive overall system simulation infrastructure may reduce the amount of required tools, and thereby accelerate and join the development process of technical systems. With the Experimentable Digital Twin, a virtual prototype becomes available whose level of detail increases successively while virtual test results give a sufficient reliable statement about the design quality and reduce the number of usually expensive hardware prototypes.

Rapid advances in new generation information technologies, such as big data analytics, IoT, edge computing and artificial intelligence, have nowadays driven traditional manufacturing all the way to intelligent manufacturing. Intelligent manufacturing is characterised by autonomy and self-optimisation, which proposes new demands such as learning and cognitive capacities for manufacturing cell, known as the minimum implementation unit for intelligent manufacturing. In this context, [20] proposed a general framework for knowledge-driven digital twin manufacturing cell (KDTMC) towards intelligent manufacturing, which could support autonomous manufacturing by an intelligent perceiving, simulating, understanding, predicting, optimising and controlling strategy. Three key enabling technologies including digital twin model, dynamic knowledge bases and knowledge-based intelligent skills for supporting the above strategy were analysed, which equip KDTMC with the capacities of self-thinking, self-decision-making, self-execution and self-improving. The implementing methods of KDTMC are also introduced by a testbed. Three application examples about intelligent process planning, intelligent production scheduling and production process analysis and dynamic regulation demonstrate the feasibility of KDTMC, which provides a practical insight into the intelligent manufacturing paradigm.

In recent years, the literature has paid considerable attention to digital twin technology for the implementation of Industry 4.0 and intelligent manufacturing. Most of the literature argues that simulation models are a key platform for digital twins and considers discrete-event simulation to be a suitable method to model real dynamic manufacturing systems. However, the discrete-event simulation of complex manufacturing systems is a time-consuming process. Therefore, it is difficult to deal with the large-scale discrete optimisation problems in digital twin shop floors. To bridge this research gap, [19] proposed an improved multi-fidelity simulation-based optimisation method based on multi-fidelity optimisation with ordinal transformation and optimal sampling (MO2TOS) in the research. The proposed method embeds heuristic algorithms to accelerate the solution space search efficiency in MO2TOS. Moreover, an improved simulation-based optimisation system was developed, by integrating the proposed method with discrete-event simulation tools. This system is, then, applied to a digital twin-based aircraft parts production workshop. Based on this digital twin infrastructure, different production planning experiments were conducted, in order to evaluate the performance of the proposed method. The experimental results demonstrate that the proposed improved multi-fidelity simulation-based optimisation method is well-applied in solving large-scale problems and outperforms other simulation-based approaches.

Based on the aforementioned works, Table 1 clusters the studied references in some application domains of digital twins (industry, communications, and IoT/networks/protocols), that can be related to instrumentation systems.

Finally, we can summarize the following contributions of this paper regarding to the literature review:

- The investigation of digital twins applied to the instrumantation networks;
- The proposed self-regulation scheme, which considers the digital twins concept to evaluate the quality of data collected by physical sensors;
- A low-cost implementation of the proposed self-regulation system, followed by real experiments conducted by a case study;
- The evaluation of the proposed system by means of a data aggregation scheme, with a median filter.

Table*1* List of references for application domains of digital twins, related to instrumentation systems.

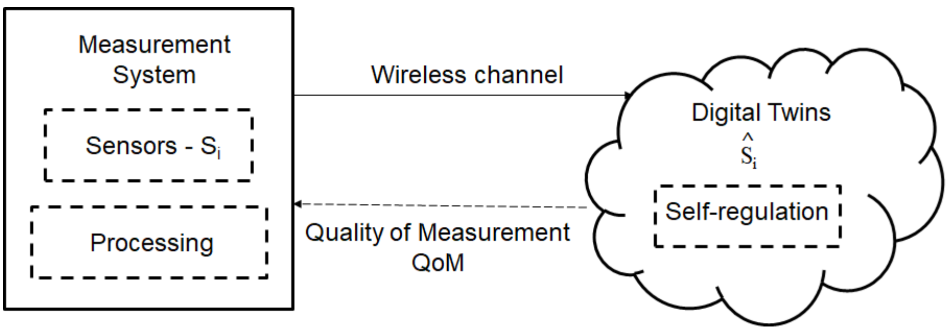
Digital Twin Aplication	Reference
Industry	[8], [14], [15],[19], [20]
Communications	[1], [13]
IoT, Networks, Protocols	[1], [3], [4], [13], [15]

IV. SELF-REGULATION SYSTEM AND CASE STUDY

4.1 Proposed Model

Figure 1 presents the proposed model of an instrumentation system in the context of Internet of Things, containing the self-regulation mechanism based on the concept of digital twins.

Figure*1*. Model scheme of the proposed instrumentation system with the digital twins-based self-regulation.



In the proposed system, each sensor (S_i) that composes the instrumentation system has a virtual replica, a digital twin, at the cloud ($\widehat{S_i}$), which receives, through the wireless channel, the samples collected and/or processed from the monitored signal. In this context, instances of the digital twin can be created in order to analyze the received data and the functioning of the physical twin. A criteria proposed by us, called the Quality of Measurement (QoM) in this work, which depends on the application of the instrumentation system, is used in the virtual space to evaluate the real sensor, and can be considered to evaluate the inaccuracy of a given physical twin. For example, several methods of reconstruction of a received coded signal can be evaluated in parallel by digital twin instances, in order to indicate if the used compression (or aggregation) rate needs to be adjusted; in other example, if the measurements collected by the real sensor are very noisy, generating a high variance (which can be identified by the digital twin), a message can be sent to the physical twin indicating that it could use a median filter (or other method) to smooth the collected signal; in another perspective, if the digital twin senses that the energy of its real pair is below a certain acceptable limit[1], a message can be sent indicating that the physical sensor should slow down its transmission rate, or compresses the data at a higher rate than the current one.

Consders that the measurements acquired by sensor S_i are organized as a vector $x_i = [x_i(1), x_i(2), \ldots, x_i(N)]$, and these data are sent to the digital twin at the cloud, generating the vector $y_i = [y_i(1), y_i(2), \ldots, y_i(K)]$, $K \leq N$ (some of the samples can be lost due to the wireless channel). Thus, as aforementioned, the QoM can be defined as a metric $Q_i\{.\}$ that evaluates the physical sensor from data received at the virtual space.

4.2 Case Study

In this experiment, a low-cost instrumentation system composed of temperature and humidity sensor modules, microcontroller and radio was implemented, thus developing a monitoring (instrumentation) system, presented in Figure 2. The sensor used in the experiment was the temperature and relative humidity sensor DHT11. The microcontroller chosen for this case study was the ESP8266. The choice of this microcontroller was due to its Wi-Fi connectivity and mobility capabilities.

In order to obtain communication with the cloud, the IoT ThingSpeak[2] platform was used, which allows to aggregate, visualize and analyze data flows, in a very simple way. One of the advantages of this platform is the possibility of viewing the data sent by the devices, in real time, in addition to allowing analysis through the MatLab[3] software. Thingspeak is a free platform, and data is sent via HTTP/HTTPS.

Figure 2. Photo of the experiment, conducted in the case study.

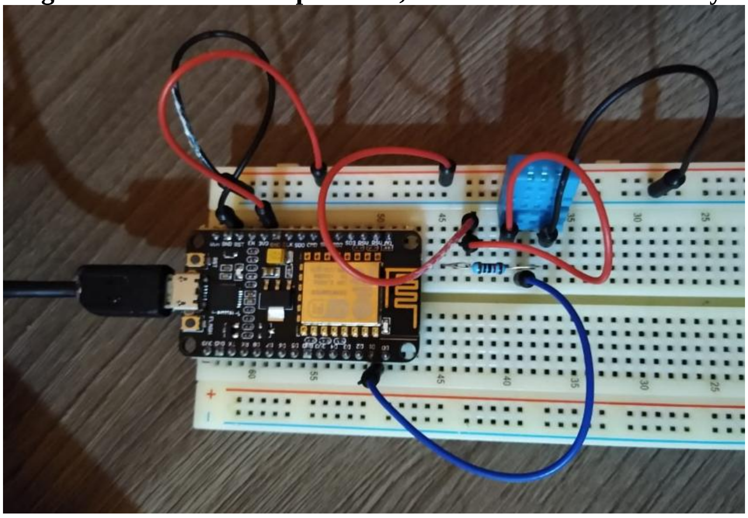


Figure 3 shows the screen of the cloud IoT platform, ThingSpeak, showing the quantities measured by the temperature and humidity sensors, that were received at the cloud by the digital twin. In this experiment, samples were collected and transmitted at every 30 seconds.

This experiment presented, in a simplified way, the proposed instrumentation system. In this scenario, temperature and humidity sensors collected data at every 30 seconds. Data was sent to the cloud through the Wi-Fi interface of the ESP8266 microcontroller. Upon receiving the signal, the sensors' digital twin was able to indicate that the monitored signals could be smoothed through a median filter. Figures 4 and 5 present the temperature and humidity signals, respectively, along with their filtered versions.

Regarding to the data aggregation procedure, in general, local processing allows greater speed to the process, since data is processed directly by the physical sensor, but with a higher energy cost and memory required for this sensor. On the other hand, cloud processing allows for a lower computational cost on the part of the sensor nodes. However, it generates a higher delay in the network response (from the cloud to the sensor node), in addition to requiring an Internet connection.

[1] Information about residual energy from the physical sensor can be sent to the digital twin from time to time.
[2] https://thingspeak.com/
[3] https://www.mathworks.com/products/matlab.html

Figure 3. Screen of the ThingSpeak platform, showing data monitored bi the digital twin, at the cloud.

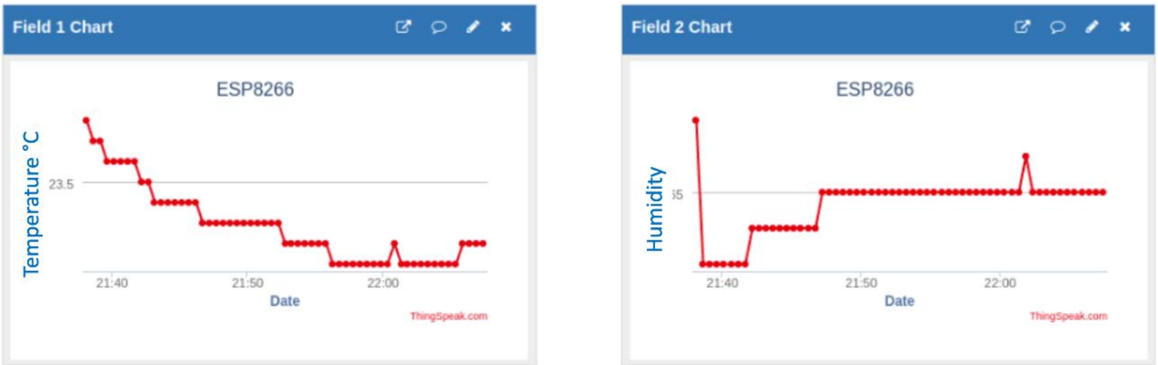


Figure 4. Temperature signal collected and filtered (with median filter).

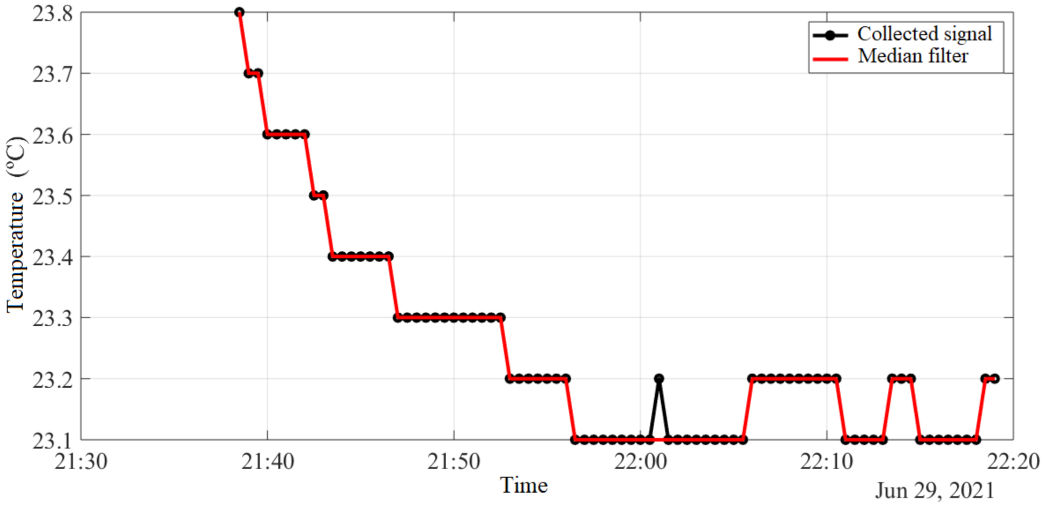
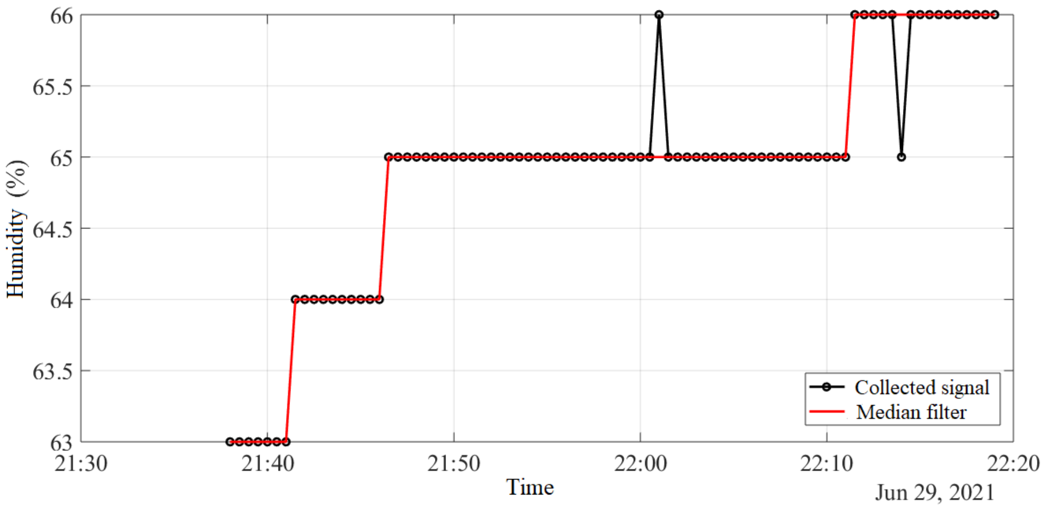


Figure 5. Collected and filtered humidity signal (with median filter).



Nevertheless, in our envisioned self-regulation system, the ideia is that the psysical sensor, initially, acquires and transmits the raw data (without processing) to its digital twin (at the cloud). Doing so, it is not necessary to perform any previous processing task, saving sensor's energy. The digital replica (at the cloud), then, receives these data from their physical twin and can evaluate the quality of the measurements (QoM), based on $Q\{.\}$, being able to verify possible erros, noise, unacceptable variations, or even to perform data prediction. After that, if some of these issues is detected, the digital sensor can send a message to their physical twin requesting some data processing, such as aggregation, compression, or other methods. In this work, data aggregation is performed, with a median filter, in order to smooth the signal.

V. CONCLUDING REMARKS

In this work, a low-cost instrumentation system consisting of the temperature and relative humidity sensors DHT11, the microcontroller ESP8266 with Wi-Fi radio, along with the ThingSpeak cloud computing IoT platform was implemented, thus developing a monitoring system. We proposed a self-regulation scheme, based on digital twins concepts, in order to evaluate the quality of the measurements collected by the sensors. The developed system was implemented in a real scenario, and analyzed in a case study. This experiment presented, in a simplified way, the proposed instrumentation system, with data collected every 30 seconds. The data were sent to the cloud through the Wi-Fi interface of the ESP8266 microcontroller. Upon receiving the signal, the digital twin of the physical sensors was able to indicate that the monitored signals could be smoothed through a median filter, indicating the feasibility of the proposed instrumentation system.

For future works, we intend to investigate other data aggregation methods, such as the fuzzy-based ones and others that consider semantic correlation among distinct sensors. In addition, more experiments must be conducted, in order to evaluate the impact of the abovementioned methods on the self-regulation system.

Conflict of interest

There is no conflict to disclose.

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REFERENCES

[1]. Ala-Laurinaho, Riku et al. Data Link for the Creation of Digital Twins. IEEE Access, v. 8, p. 228675 – 228684, 2020.
[2]. Aquino, Gabriel Rodrigues Caldas de; Farias, Claudio Miceli de; Pirmez, Luci. Data Quality Assessment and Enhancement on Social and Sensor Data. In: BIDU-POSTERS@ VLDB. [S.l.: s.n.], 2018.
[3]. Autiosalo, Juuso et al. Twinbase: Open-source server software for the Digital Twin Web. IEEE Access, v. 9, p. 140779 - 140798, 2021.
[4]. Dahmen, Ulrich and Rossmann, Juergen. Experimentable Digital Twins for a Modeling and Simulation-based Engineering Approach.IEEE International Systems Engineering Symposium (ISSE), 2018
[5]. De Farias, Claudio M. et al. A multi-sensor data fusion technique using data correlations among multiple applications. Future Generation Computer Systems, v. 92, p. 109–118, 2019. ISSN 0167-739X. DOI: https://doi.org/10.1016/j.future.2018.09.034.
[6]. Delicato, Flávia C et al. Heracles: A Context-Based Multisensor Sensor Data Fusion Algorithm for the Internet of Things. Information, Multidisciplinary Digital Publishing Institute, v. 11, n. 11, p. 517, 2020.
[7]. Diène, Bassirou et al. Data management techniques for Internet of Things. Mechanical Systems and Signal Processing, v. 138, p. 106564, 2020.
[8]. Dli, Maksim et al. Energy and Resource Efficiency in Apatite-Nepheline Ore Waste Processing Using the Digital Twin Approach. Energies. MDPI v.13, 2020.
[9]. Grieves, M. Digital twin: manufacturing excellence through virtual factory replication. White Paper, 2014.
[10]. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. Transdisciplinary Perspectives on Complex Systems, Springer, Switzerland, 2017. ISBN 978-3-319-38754-3.
[11]. Guimarães K. P., Coelho P. H. G., Amaral, J. F., Almeida N. N., Fonseca A.C.X.S. "Application of Fuzzy Inference Systems in the Transmission of Wireless Sensor Networks". 19th International Conference on Enterprise Information Systems - Volume 1: ICEIS, 618-624, 2017.
[12]. Moris, A.S. E. "Measurement & Instrumentation Principles". Butterworth-Heinemann. 3rd edition. 2001.
[13]. Nguyen, Huan X. et al. Digital Twin for 5G and Beyond. IEEE Communications Magazine, v. 59, p. 10-15, 2021
[14]. Qamsane, Yassine et al. A Unified Digital Twin Framework for Real-time Monitoring and Evaluation of Smart Manufacturing Systems. IEEE 15th International Conference on Automation Science and Engineering (CASE), 2019.
[15]. Qi, Qinglin and Tao, Fei. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. IEEE Access, v. 6, p. 3585 - 3593, 2018.
[16]. Shaikh, Asadullah; Alaghamdi, Abdullah. IoT, smart environments and interdisciplinary applications for technology management and sustainable development. International Journal of technology management & sustainable development, v. 19, n. 3, 2020.
[17]. SINGHAL, Deepti; GARIMELLA, Rama Murthy. Simple Median based information fusion in wireless sensor network. In: IEEE. 2012 International Conference on Computer Communication and Informatics. [S.l.: s.n.], 2012. p. 1–7.
[18]. Sundmaeker, Harald et al. "Vision and challenges for realising the Internet of Things". Strategic Research Agenda, European Commision, v. 3, n. 3, p. 39-82, 2010.
[19]. Zhang, Zhengmin et al. Improved multi-fidelity simulation-based optimisation: application in a digital twin shop floor. International Journal of Production Research, 2020.
[20]. Zhou, Guanghui et al. Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing. International Journal of Production Research, Vol. 58, No. 4, 1034–1051, 2020.