Modular Data Acquisition Architecture for Thin-Film Sensors Surfaces

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***Abstract*—Thin-film sensors surfaces are becoming popular to collect data in several specific and complex processes, namely plastic injection or metal stamping, allowing the digitization of such processes through the use of Internet of Things technologies. A particular challenge in such thin-film sensors surfaces is the data acquisition and signal conditioning system, which implementation is complex due to the characteristics of these sensors (e.g., low amplitude and noisy signals), but even more complex when implemented in real industrial processes, which are subject to harsh conditions, namely noise, dirt and aggressive elements. This work describes a modular data acquisition and signals conditioning system for thin-film sensors surfaces, meeting the requirements of scalability, robustness and low-cost, meaning that it can be easily expanded according to the number of sensors required for the application scenario.**

Keyword: Data Acquisition and Signal Conditioning, Thin-film Sensors Surfaces, Industry 4.0.

I. Introduction

Data is a crucial pillar in the Industry 4.0 era, being required its acquisition, transmission, storage and analysis aiming to perform, amongst others, monitoring, diagnosis, prediction and optimization. As examples, the real-time data collection and analysis allows to monitor the machinery and process condition, and to predict in advance future failure occurrences, supporting the optimized planning of maintenance interventions to mitigate the occurrence of such failures and consequently contributing to increase the useful life of machines, reducing the machine downtime and reducing the maintenance costs [1].

Data can be automatically and real-time collected using sensorial systems complemented with Internet of Things (IoT) technologies. One important area, which is being explored in the On-Surf project [2], is the development and application of advanced solutions in surface modification processes, particularly, developing thin surfaces with particular characteristics, namely self-lubricating, decorative, non-stick and sensorial. Especially, the sensorial surfaces are based on thin-film sensors that are useful to measure several parameters, e.g., temperature or pressure, in complex shapes. In this case, the complex structure is coated with a sensory thin-film surface, e.g., a piezoresistive thin-film sensor, where the reaction to mechanical deformations changes the electrical resistance, allowing to measure the parameters along the surface. This type of thin-film sensors can be applied in different applications, namely biomedical devices, automotive and molding. One example of its application is the metal stamping industrial processes, where thin-film sensors are used to gather real-time data, e.g., temperature and pressure. The collected data supports the monitoring of the process execution, e.g., regarding the quality assurance and the earlier detection of deviations that allows to perform adaptation and optimize the manufacturing process, providing a competitive advantage [3].

The development of such thin-film sensors surfaces comprises several important challenges. Firstly, it requires a complex set of methods and tools to create a thin-film sensor by the deposition of the piezoresistive physical layer (e.g., around the µm and nm scales), combined with the wear resistance layers [4]. Secondly, after guaranteeing the correct variation of the sensor (ohm delta), it is necessary to ensure that the routing of the signal conductor cables off the surface to the signal acquisition system does not distort the signal values. And finally, the implementation of the data acquisition and signal conditioning system that should ensure the proper acquisition of the signal (amplification, filtering, conversion, etc.), supporting the posterior monitoring and analysis.

Focusing the data acquisition and signal conditioning system challenge, this process becomes more complex when implemented in real industrial processes, which is subject to harsh conditions, namely noise, dirt and aggressive elements. On the other hand, thin-film sensors impose other constrains, particularly focusing on the difficulty in the connection to the acquisition system. The characteristics of the sensor and the metal they cover do not allow welding wires or connectors to its terminals, and the vibration of the industrial equipment can be a source of bad contacts influencing the quality of the measurements. Additionally, these sensors are custom made having different calibration needs, either in terms of span offset or even linearization, which should be carried out on industrial equipment at the factory.

Having this in mind, this paper describes the development of the data acquisition and signal conditioning system, adapted to the requirements and challenges of thin-film sensors surfaces. The proposed innovative system architecture features a modu-

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lar, scalable and robust approach, comprising several modular modules that allow being expanded according to the number of sensors and parameters to be measured by the surface of the thin-film sensor. The acquisition and conditioning system is being installed in an industrial case study regarding a plastic injection process, considering the measurement of temperature and pressure parameters.

The remaining of the paper is as follows: Section II overviews the related work on acquisition and conditioning systems in thin-film sensors surfaces. Section III presents the developed system architecture for data acquisition and signal conditioning, and Section IV presents the preliminary experiments and discusses the achieved results. Finally, Section V rounds up the paper with the conclusions and points out some future work.

II. Data Acquisition and Signal Conditioning in Thin-film Sensors

Process data acquisition is playing a significant role in Industry 4.0, which uses sensors to collect data regarding the condition operation of machines and processes, allowing to predict failures' occurrence in advance, increasing efficiency and reducing operational risks [5]. In this context, the manufacturing industry takes advantage of integrating thin-film sensors in its processes. The industrial mold sector, which has metallic stamping and plastic injection processes, uses thin-film sensors to acquire different operating conditions, such as pressure, temperature and deformation [1]. What differentiates thin-film sensors from conventional sensors is that in addition to the typical sensor functions, they can also be elements of data, energy-transmission and can be incorporated in direct contact with the part, which allows measurements to be carried out with greater precision [6].

In this context, thin-film sensors are promising solutions for measurement, such as surface strain and temperature, in the process of metal formation and plastic injection, as they can be flexible enough for these applications, allowing the real-time data acquisition and the development of low-cost technological solutions [7], [8].

Recently, different types of applications using thin-film sensors are being explored by the scientific community in industrial applications. Examples are the monitoring of cutting forces in a milling process [7], the wireless acquisition of the temperature in tools [6], and the monitoring of tool wear [9]. However, the use of thin-film sensors surfaces requires reliable systems for the conditioning of the acquired signal. In fact, a major challenge in the industry is the reliability of the data acquired due to a large number of "environmental" variables that can influence the behaviour of the sensors, which makes the signal acquisition and conditioning process complex. Additionally, the film thickness is thin (e.g., less than hundreds of nanometers) and the small size of the sensor makes it more prone to electromagnetic and thermal noise interferences [6].

Usually, data acquisition and signal conditioning use traditional data acquisition boards that provide reliable solutions but lacks in terms of providing other essential characteristics. In particular, such solutions should exhibit modularity (i.e. being composed of pluggable modules, that permits to builds larger systems by combining smaller subsystems), scalability (i.e., the ability to grow the system components without extra resources) and robustness (i.e., the capability of tolerating perturbations/variations). Additionally, low-cost solutions and approaches that allow easy and fast configuration are also desirable.

III. System Architecture for the Data Acquisition and Signal Conditioning

The proposed architecture for the data acquisition and signal conditioning in thin-film sensors surfaces is illustrated in Figure 1, addressing relevant industrial requirements like modularity, scalability and robustness. Such architecture permits to scale the number of sensors according to the application needs, providing parameters' measurements about the process that allows to monitor the process condition, predict possible failures in advance and optimize the process operation.

The system architecture comprises four modules, namely the signal conditioning, the signal conversion, the data concentrator, and the visualization. Briefly, the first module is responsible for performing the signal conditioning, namely amplifying and compensating the signal. The signal conversion is responsible for the conversion from analogue to digital, aggregating the signals from several sensors, which are posterior concentrated and stored in a database located at the Cloud for posterior analysis. The data concentrator is also responsible for synchronizing the different devices connected to the network using a Network Time Protocol (NTP) server, ensuring that the sensor measurements are not lagged in time. Finally, the visualization module allows the monitoring of the collected data in a dashboard.

The implementation of the architectural modules is detailed in the next subsections.

A. *Signal Condition*

One objective of the On-Surf project is the acquisition of temperature and pressure signals from thin surfaces coated to molds during the plastic injection processes. The signal-conditioning plays a crucial role in any data acquisition system, being constrained by several challenges when applied to thin film sensors, namely the film thickness, the harsh industrial conditions, the different sensors' characteristics, and should exhibit modularity, scalability, robustness and availability features. This may result in a significant timely and costly design, configuration and development of such solutions. Having this in mind, the acquisition system must be carried out in a fast manner with a modular and low-cost approach that also supports its easy reconfiguration according to the application needs in the industrial environment.

In this context, it was decided to use a conditioning system based on a single chip, the ZSSC4151 sensor signal conditioner (SSC) developed by IDT Renesas. The ZSSC4151 provides highly accurate amplification and sensor-specific

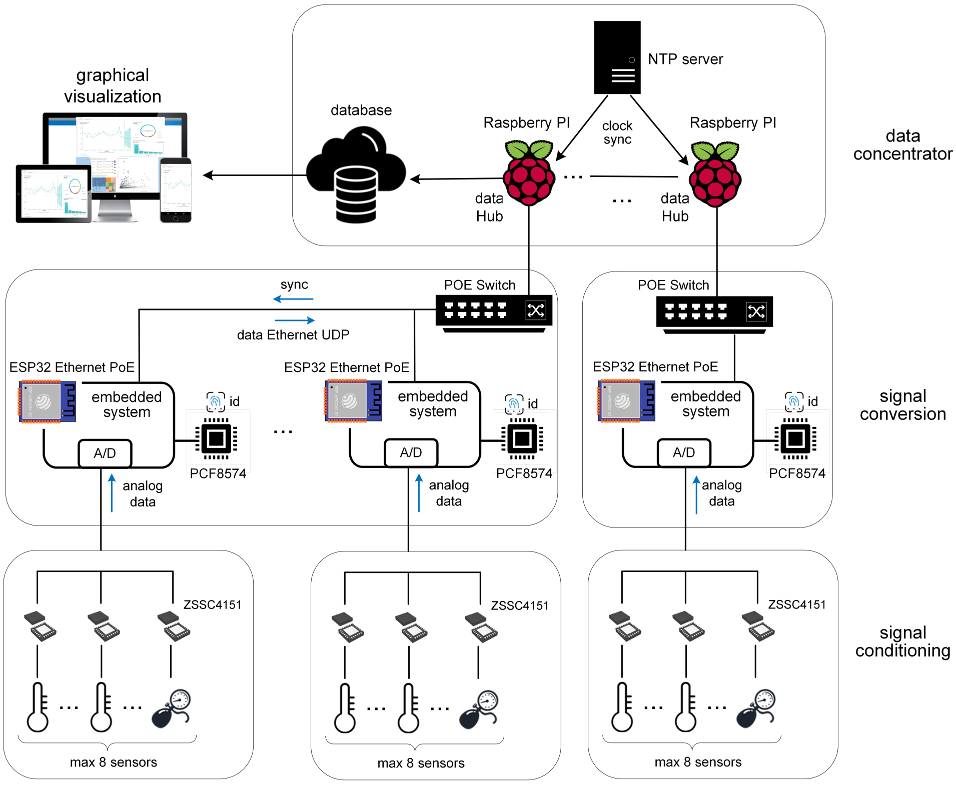

Figure 1: Architecture of the data acquisition and signal conditioning system.

correction of bridge sensor signals [10]. The provided functions, namely digital compensation of sensor offset, sensitivity, temperature drift, and non-linearity, are performed through the use of an internal 16-bit RISC microcontroller running a correction algorithm with calibration coefficients stored in an on-chip EEPROM by using the digital I2C protocol. The calibration coefficients for the specific sensor can be easily and quickly calculated by using a proper application, where the ZSSC4151 and the calibration equipment communicate in a digital manner, allowing the significant reduction of the noise sensitivity.

Once this digital calibration process is done for the several temperature and pressure sensors, i.e. for the several ZSSC4151 - sensor pairs, these are ready to be used, which means that the acquired signal is amplified, conditioned and compensated by this integrated circuit. In the end, the conditioned signal is sent to the signal conversion module, i.e., to the ESP32-Ethernet-PoE A/D converter input where each ZSSC4151 – sensor pair is connected.

B. Signal Conversion

Having in mind the modularity and scalability requirements, the signal conversion module was developed to allow combining the signals from the different number of sensors and adding easily more modules. For this purpose, this module uses several ESP32-Ethernet-PoE (from now on, referred as ESP32) as an embedded system, each one supporting up to 8 signals (e.g., temperature and pressure parameters). Aiming to reach the modularity, each ESP32 has coupled a remote 8-bit I/O expander for I2C-bus device (i.e.PCF8574) that aims to identify each microcontroller address, allowing to build a matrix of data collected from the several sensors. In fact, this I/O expander also allows defining the last octet of the interface IP address. In this way, it is easy to insert and identify new modules into the same acquisition system according to the scalability concept. The conversion from analog to digital is performed with the ESP32 12-bit successive approximation with a reference voltage of 3.3V. Once the connection is not performed by Wi-Fi but Ethernet, both internal analog to digital converters ADC1 and ADC2 can be used.

The converted data is sent to the switch via Ethernet UDP communication using the unicast scheme. On the other hand, the synchronization commands, coming from the data concentrator, are forward to the ESP32 devices through the switch using a multicast scheme. To solve the complexity of connecting the sensors, it was selected the Power over Ethernet (PoE) technology. The PoE switch allows data and power to be transmitted over an Ethernet cable at the same time. It allows an easy connection to the network, supporting the adaptation of the number of acquisition modules without extra hardware, permitting to save money with the number of power adapters that would be needed in a different solution.

C. Data Concentrator and Visualization

The data concentrator is based on a Raspberry Pi (RPI) that establishes an intermediate level between the lower signal conversion layer (based on ESP32 devices) and the upper layer (i.e., the Cloud). This organization allows having these modules dedicated to performing a small set of tasks, namely to send synchronism packages to the lower-level modules, ensuring that their internal clocks maintain the synchronism. Otherwise, the synchronism would be lost due to the clock drift, and the acquired signals would present lags affecting the acquisition process. At the same time, packets are marked with a timestamp derived from the synchronism data, which solves the problem of irregular packets distribution on the communication and the problem regarding the out-of-order delivery.

Another task is to establish a buffering mechanism between the UDP protocol that deals with the lower signal conversion layer and the TCP protocol that deals with the upper layer (i.e., Cloud). This UDP/TCP buffer is based on a large amount of memory, for communications, which inhibits the loss of UDP (unregulated flow) packets, caused by the RPI CPU loading. This loading is aggravated by the parallel sending of TCP packets (regulated flow). In the absence of the RPI level, one would have to assume that non-dedicated modules in the Cloud would be sufficiently capable of meeting the UDP data flow generated by a large number of sensors on time; but this imposes scalability problems for the Cloud and consequently higher costs. In the same direction, one can assume the lower level modules could work in TCP as long as their communication memory buffer was sufficiently large, which in practice is not the case with the ESP32 devices. Moreover, ESP32 cannot be replaced by RPI, since ESP32 works with real-time operations, which leads to phase stability during the signal acquisition, while RPI's operations are non-real-time and then can not be guaranteed the same stability at that stage. Besides, with the use of this RPI level, it is possible to increase the number of RPI modules horizontally, offering a low-cost solution to solve the issue of scalability provoked by the densification of UDP and TCP packets.

Regarding the in situ signal visualization, this level simplifies that process when compared to the usage of an approach derived from the Cloud. All the data is being passed through the RPI, so, using an intelligent downsampling method and a suitable graphic display, the human operator can immediately observe the signal evolution for taking measures about some process anomalies. In parallel, the RPI also sends the collected data to a MongoDB database, hosted in the Cloud, allowing the visualization and monitoring of the collected information but also support the execution of data analytics methods to optimize the process being monitored.

IV. Preliminary Experiments

This section presents some preliminary experimental tests performed during the implementation of the data acquisition for the thin film sensors in the industrial case study.

A. Case Study

The developed data acquisition and signal conditioning system is being used to collect data from the temperature and pressure sensors embedded in a thin-film sensors surface installed in an industrial plastic injection process, as illustrated in Figure 2.

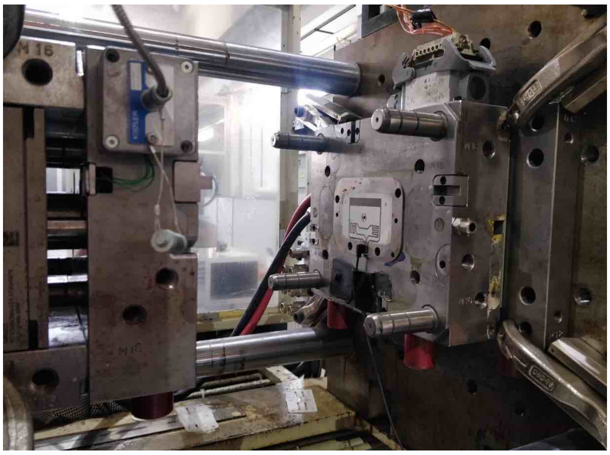

Figure 2: Plastic injection process case study.

The plastic injection process considered in this work takes place every 32 seconds, with the sensors collecting the injection pressure and temperature parameters. In detail, during 30 seconds, the mold is closing, which corresponds to the plastic going through several resistances to become a fluid, so that it can then be injected into the mold. The injection process, performed at approximately 20°C, is related to the phase when the plastic fluid reaches the mold and the cooling occurs. During the injection time, approximately 2 seconds, the two most important values of the measurement will occur, i.e., the highest temperature value and the highest pressure value (approximately 40 bar with a standard deviation of 2 bar). As this process happens quickly in a short time, the acquisition sample rate must be as high as possible.

After the injection process, the mold opens, and naturally, the pressure value decreases, returning the mold to the initial position (see Figure 2). During this phase, the temperature of the mold approaches 35°C.

B. Characterization of the Temperature and Pressure Sensor

In this work, the mold used in the plastic injection process is coated with a thin-film sensors surface, which allows the collection of temperature and pressure data in a specific point [4]. The development of the data acquisition system requires a previous study and characterization of each sensor that is collecting data, aiming to support the proper signal conditioning, especially when these sensors are custom made, having different calibration needs, whether in terms of amplitude offset or even linearization.

The test bench for the sensor characterization, illustrated in Figure 3, consists of several steps to predict the behavior of the sensor, that will support its digital calibration and the subsequent configuration of the ZSSC4151 SSC. The ZSSC4151 configuration was performed by using the Sensor Signal Conditioner 4151 application [10], provided by IDT, and its data acquisition card.

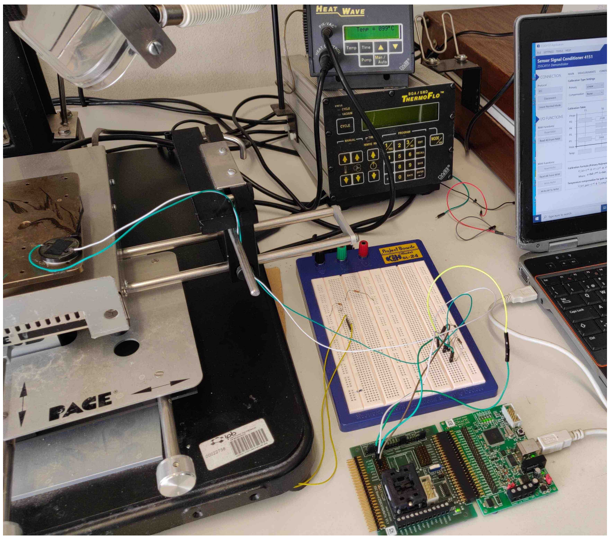

Figure 3: Thin-film sensor to measure temperature and pressure, and the IDT application to configure the ZSSC4151 SSC.

Initially, the ZSSC4151 is placed inside the 24-QFN socket in the IDT acquisition card, which is connected to a PC, allowing the recognition of the ZSSC4151 device by the Sensor Signal Conditioner 4151 application. The calibration process is accomplished by inputting stimulus at the sensor and collecting the responses from the sensor that will be calibration points (see Figure 4) Considering the temperature curve calibration, several points are collected for different temperature values. The number of calibration points required to create the calibration curve depends on the behaviour of the sensor. For instance, if the behaviour of the sensor follows a linear calibration, only two points are required, i.e., P1 and P2 related to the sensor output for the highest and lowest temperature. Moreover, the IDT application allows selecting different types of calibration, which can be based on linear, quadratic or cubic regressions.

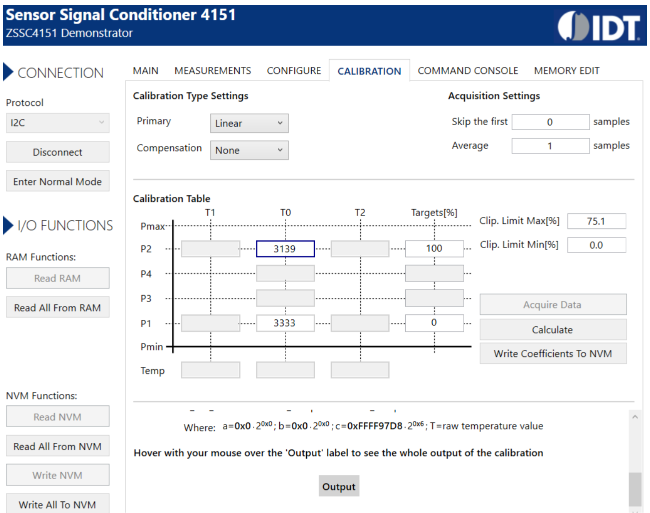

Figure 4: Screenshot of the configuration application.

After this process, the application software calculates the calibration and compensation formulas that are written in the flash memory of the integrated circuit ZSSC4151 by using the I2C protocol. Figure 5 illustrates the calibration curve for the exemplary temperature sensor tested in this work. The respective equation, also provided by the IDT data acquisition application, is used by the ZSSC4151 to make the signal conditioning.

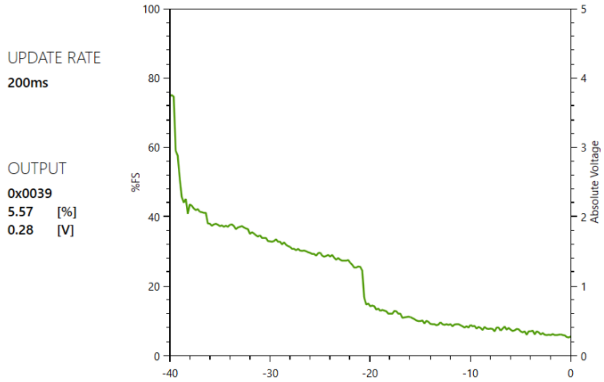

Figure 5: Calibration curve for the temperature sensor.

C. Data Acquisition, Conversion, Transmission and Storage

In terms of robustness, it was possible to verify that each conditioning module can support up to eight sensors simultaneously with a 1 kHz sampling frequency according to the industrial case study requirements (see the case study description). Mainly, using the Wireshark software [11], it was possible to verify that the average network throughput is 2000.8 packets per second (pps), representing only one sensor with a double redundancy to ensure redundancy and to prevent packet loss along the way, resulting in a total of 124 bytes per package, which results in 248.099 B/s in total. Therefore, the acquisition system is collecting approximately 851.8 MB per hour and sending it to the RPI, which means approximately 6.8 GB per each 8-hour shift. The RPI analyses the received data and removes the redundancy (duplicated packages), resulting in approximately 3.4 GB data per shift to be saved in the MongoDB's Cloud-hosted database.

The experimental tests also showed that there is no loss of packages during the transmission of data, demonstrating the reliability and robustness of the proposed approach.

D. Pluggability, Modularity, Scalability and Availability

Several other tests were performed to verify the architectural characteristics of the proposed solution, namely in terms of modularity, pluggability, scalability, and availability.

In terms of pluggability, the proposed architecture aims to ensure that the addition of new elements to the system is performed without the need to perform network configurations. The RPI IP addresses are obtained dynamically using a Dynamic Host Configuration Protocol server. Each pyramidal branch of the stack circuit is supported by different Ethernet network segments, allowing multicast communications to be contained with a single static IP address for each new network segment. The PoE power also contributes to this plug and play simplification by allowing to distribute the power to the various modules (e.g., ESP32 and RPI modules) without specific settings and electric overloadings. The ESP32 modules are identified by an ID that is chosen easily during the installation and set by a rotary switch in a range of 256 different values.

Accompanying the plug and play feature is the modularity feature. New branches are easily added to each level of the system tree. The limit for this addition is related to the number of different IDs, i.e., 256, on the terminator ESP32 modules. Placing 256 modules in the system allows having 256x8 sensors, corresponding to more than 2000 sensors). Each ESP32 data communication requires an ethernet bandwidth of 2 Mb/s, which is noticeably below to the 100 Mb/s limit on the 100BASE-TX ethernet interface present in the ESP32 module. The bandwidth capacity of the RPI interface is 1 Gb/s, allowing, in this domain, to reach 500 devices in a single hub. However, the multitasking processing capacity that the RPI presents does not allow this number. Thus, it was estimated that the maximum number of ESP32 modules connected to each RPI concentrator, to avoid the bottleneck effect on the data flow, is eight units. This estimation considered the memory limit allocated to the network sockets and the RPI processing time for each data frame. This limitation is solved by the addition, horizontally, of new RPI concentrators, and respective acquisition ESP32 modules. Thus, the number of sensors can reach again 2000 sensors.

The availability, maintenance and redundancy are also essential characteristics of the proposed architecture, which allows, by the simple addition of modules, gaining redundancy and, consequently, obtaining the system availability even during the maintenance periods. As they are relatively low-cost modules, the system can be scaled to address the availability, maintenance, and redundancy issues without worrying about cost restrictions. The low consumption of these modules also allows neglecting the cost of the system facing the scale augmentation.

V. Conclusions

Thin-film sensors have become an interesting approach to measure data regarding the industrial process operation, contributing to the digitalization of such systems. The diversity of applications drives the interest of this work in designing a system architecture capable of executing the data acquisition and signal conditioning system for such thin-film sensors that imposes particular and demanding requirements, contributing to the posterior dynamic monitoring of measured parameters.

The proposed approach for the data acquisition and signal conditioning is modular, scalable, and robust, comprising four layers, which can be easily expanded depending on the number of sensors required for the application scenario. The first layer is responsible for the conditioning of the signals acquired from the temperature and pressure sensors, and the second layer, which is based on ESP32 microcontrollers, is responsible for aggregating several data sources and converting the data from analog to digital. The third layer is a concentrator hub that is responsible for synchronizing the clock of the ESP32 modules, filtering the data redundancy, and sending it to be stored in a Cloud-based database, which can be used later for monitoring and optimization purposes.

The proposed approach offers several important characteristics, namely pluggability, modularity, scalability, availability, and robustness, addressing important industrial requirements, mainly related to plastic injection processes. Another important feature is the possibility of developing this modular and system at low-cost. In fact, a solution comprising 8 sensors has a cost of approximately 164€, and the extension to 16 sensors only has an increase of approximately 30%, which is significantly lower than a typical data acquisition system.

Future work will be devoted to extending the experiments with a higher number of sensors and considering the operation of the thin film sensors surface in the industrial process, facing industrial environments subject to noise, dirt, and aggressive elements. Additionally, data analysis algorithms, using machine learning methods, will be developed to perform dynamic monitoring and optimization of the plastic injection process.

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