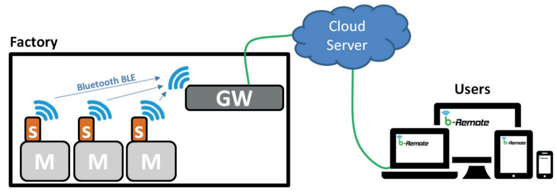
A new simple, flexible and low-cost machine monitoring system



Desarollo de un nuevo sistema sencillo, flexible y de bajo costo para monitorización de máquinas

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RESUMEN

- La revolución de la industria 4.0 proporciona a las máquinas una capacidad sensorial y comunicativa, lo que les permite monitorear y recolectar grandes cantidades de datos. Estés tienen un impacto en la planificación, el mantenimiento y la gestión de la producción, permitiendo la reacción en tiempo real, el aumento de la eficiencia y el desarrollo de modelos predictivos y de mejora de procesos. Las máquinas más recientes están preparadas para comunicarse con los sistemas de monitoreo existentes, sin embargo, muchas aún no lo hacen (cerca de 60%).
  El objetivo de este trabajo es presentar la propuesta de un sistema de monitoreo remoto de equipos en tiempo real que cumpla con los requisitos de bajo costo, sencillez y flexibilidad. El sistema monitorizará de forma sencilla y ágil, independientemente de su sofisticación, limitaciones de instalación y recursos de la empresa.
  Se desarrolló y probó un prototipo de un sistema tanto en condiciones de laboratorio como en un entorno productivo. La arquitectura propuesta del sistema consta de un sensor que transmite la señal de la máquina de forma inalámbrica a una puerta de enlace que es responsable de recopilar todas las señales circundantes y enviarlas a la nube. Durante la prueba y evaluación de las herramientas, los resultados validaron el prototipo desarrollado.Como resultado principal, la solución propuesta ofrece un nuevo sistema de monitoreo de bajo costo basado en tecnología madura y probada sobre soluciones flexibles y escalables.
- **Palabras Clave:** Industria 4.0, Monitoreo de máquinas, Beacon, Bluetooth BLE, Monitoreo Remoto, Bajo costo, PYME's, b-Remote.

ABSTRACT

The industry 4.0 revolution provides the machines with a sensory and communicational capacity, which allows them to monitor and collect large amounts of information. This kind of data have an impact on planning, maintenance, and management of production, enabling real time reaction, efficiency increase, and the development of predictive and process improvement models. The most recent machines are prepared to communicate with the existing monitoring systems, however, many (around 60%) do not.

The objective of this work is to present the proposal of a system for remote monitoring of equipment in real time that meets the requirements of low cost, simplicity, and flexibility. The system monitors the equipment in a simple and agile way, regardless of its sophistication, installation constraints and company resources.

A prototype of a system was developed and tested both laboratory conditions and a productive environment. The proposed architecture of the system comprises of a sensor that transmits the machine's signal wirelessly to a gateway which is responsible of collecting all surrounding signals and send it to the cloud. During the testing and assessment of the tools, the results validated the developed prototype. As main result, the proposed solution offers to the industrial market a new low-cost monitoring system based in mature and tested technology laid upon flexible and scalable solutions.

Key Words: Industry 4.0, Machine Monitoring, Beacon, Bluetooth BLE, Remote Monitoring, Low Cost, SME's, b-Remote.

1. INTRODUCTION

Following the dawn of the digital age and the appearance of new Information and Communication Technologies (ICT), we are witnessing the Fourth Industrial Revolution. According to Urbikain et al. [1], the near future will require machine tools supporting highly flexible and interconnected systems, to achieve the required productivity. The availability of data to support managers decision-making, the growing connectivity between supply chain stakeholders, the appearance of knowledge based ICT systems, the increase of communication speed and amount of data without precedents are in the basis of the current industrial revolution [2, 3]. One of the most common name associated to this revolution is "*Industrie 4.0*" (I4.0), an expression firstly used by Henning Kagermann, Wofgang Wahlster and Wolf-Dieter Lukas, at the conference in the Hannover Industrial Fair of 2011 [4]. In this presentation, the authors identify a set of technological pillars which sustain the genesis of the current industrial transition.

Two of the identified pillars are Cyber Physical Systems (CPS) and the Industrial Internet of Things (IIoT). The CPS offers the innovative support for the communication and interconnection between different systems and physical components. On the other hand, the IIoT brings intelligent sensors and actuators solutions, offering improved processing and communicating capabilities [5]. These advancements in interconnection and sensoring allow profound advancements in real time remote control and monitoring of manufacturing operations and other relevant industrial functions. Everything from a production line operation to the last point of the distribution chains become connected [6]. These interconnectivity advancements also allow new developments at machine level operation. Namely, these new advancements make machine "smart", as it allows the controller to know when a sensor is faulty, a component need replacement or maintenance, avoiding potentially damage to the machine. All the information is communicated in real time, so the correct actions can be triggered [7, 8].

At industrial level, some of the most important areas where there is an urgent need for relevant data and knowledge are related with processes and resource operation improvement and optimization. Decisions and related actions must be taken quickly. To accomplish that, it is necessary to know how and when the machine/processes should be intervened, in terms of planning, setup, operation, maintenance etc. In this scope is essential to have the right data, and to have it, it is necessary to monitor processes and machines in real time [9, 10]

The continuous monitoring is essential on critical equipment's where the cost of downtime and malfunctions are too expensive or a life risk. Software dedicated to continuous monitoring and analysis of the collected data allow production and maintenance human resources detect, plan, and act accordingly, increasing the overall efficiency and life span of equipment [11].

As described in Figure 1, the monitoring can be continuous or periodic, with the objective of verify the machine operation status and the working condition. The monitoring status verifies if the machine is running or stopped, particularity the machine availability. This comprehensive equipment monitoring allows the gathering of operation status and metrics critical to the manufacturing operations. The monitoring function also gives important information that allows to increase the machine lifetime by anticipating critical fails before they occur. By knowing the condition of the machine accurately, unnecessary maintenance stops could be avoided, and replacement of parts that still have good working conditions are avoided. With this information, prediction models can be created to optimize maintenance and reduce downtimes and costs [12].

Nowadays there are in the market several systems for monitoring and managing all this information. However, the vast majority of these systems, due to their capacities, are complex and requires a specialized integration. Its operation could require dedicated employee(s). For these reasons, the costs for integration and operation can be too high for the size of certain companies. These companies dimension, could be also insufficient to take full advantage of these systems and having good cost-benefit ratios [13].

Today's factories have different types of equipment, with different operating types and communication protocols. Some of the machines are obsolete and do not have PLC (programable logic controller). Finding a monitoring system to work under these conditions becomes complex [14]. For smaller companies with simpler machines, it could be hard to find a system that fits its necessities and capacity to purchase, install and use it. Most companies are small and medium enterprises (SMEs), and despite the emergence of the Industry 4.0, these companies are far from the level of technological awareness required to implement complex Industry 4.0 systems, or don`t have the dimension to justify investment

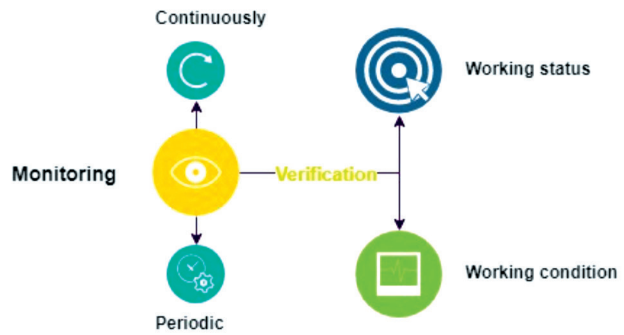


Figure 1. Monitoring types (from the authors)

in complex monitoring systems. To know the needs of the users/customers, a survey was carried out to a group of 20 SME metalworking companies located in the north of Portugal, which met the characteristics of interest and representativeness for the scope of the research. The survey revealed that 84,6% of the enquiries, have unmonitored machines, or do not monitor but would like to. A Gartner report of 2016 adds that percentage of legacy equipment worldwide at industry is around 60% in 2018 [15]. The main factors for this are the cost of existing systems, their complexity of installation and the necessity to change the software of the machines. This reality motivated the scope of this work, the development of a new monitoring system that fits the needs of these companies, focusing on cost-benefit ratio, and that could assist them in the transition to Industry 4.0. This system should comply with the following requirements:

- Easy and quick installation – without cables or software changes;
- Flexible and independent from the actual installation – compatible with any type of machine, new or old, with or without PLC;
- Simple and intuitive utilization – giving the essential information to the user;
- Accessible remotely and in real-time – from any device connected to the Internet;
- Low cost.

To achieve the goal of this work, the rest of this paper is organized as follow. Section 2 identifies the main contributions of scientific and technical solutions available in the market. Section 3 presents the general issues of the prototype design and then in Section 4 is made the evaluation of the system in laboratory and plant context. To finalize, some conclusions and future works are made in Section 5.

2. REVIEW OF THE MONITORING SOLUTIONS AVAILABLE IN THE MARKET

To develop a new system is necessary to conduct exploratory studies to obtain information about the market, namely, to identify the market requirements, to know the existing solutions, and identify the problems in order to formulate new solutions. According to Stebbins [16] the exploratory methodology has the objective of making us aware of the problem, in order to facilitate our understanding and the formulation of hypotheses.

To identify the market requirements was done a bibliographic research added to the 20 companies survey. The main results are exposed in the first column of the Table 1, mostly extracted and / or adapted from [14]. Afterwards, a market analysis was performed to identify the six major monitoring solutions available in the market. Table 1 details for each one of the select monitoring solutions the compliance or not of the selected market requirements list.

Analysing the Table 1 with complementary information obtained from the monitoring solutions, the principal conclusions are:

- The most complete solutions are, the MDC Software from Predator [17] and the MDC MAX from CIMCO [18]. These systems collect the data from the machines through serial, ethernet or wired connection, depending on the machine type. If the machine is prepared, they are ready for communication in several protocols. Their focus is CNC machines, and they are compatible with most of the manufacturers. Due to their complexity, they require integration by specialized technicians. The cost of these systems depends on the number of machines, the integration, among others. The information collected, shows that the investment for several machines is around several thousand euros, which cannot be affordable for many SME companies.
- Other solutions but less widespread include MachineMetrics software from MachineMetrics [19]. This system is very similar to the previous ones, differing in the global market disclosure. Is original from the United States and have most of its applications there. If the machines do not have a compatible protocol, is possible to add an economic PLC between machine and system gateway. Another solution is Leanworx Cloud, belonging to Leanworx Technologies[20]. It is original from India, seems complete and oriented to CNC machines, although it easily integrates signals from other machine types via non-intrusive sensors. It communicates via ethernet connection and wireless with non-intrusive sensors. These sensors, monitor relays status and send the information, via mobile network, to the server. In both systems, there is a clear need for a specialized integration. Because its costs are not available it is not possible to compare with the other solutions.
- Another solution is the EIT - Efficiency Improvement Tool from Sidel focused on status monitoring [21]. The EIT is a proprietary branded system, initially developed to the bottling and packaging production lines, expanded to address any system and production sector, presents itself as a monitoring tool to increase efficiency and reduce losses and costs. It communicates via ethernet with machines with through PLC and requires skilled technician to install and configure.
- The last one, is the simpler solution, the TC Mobile from Phoenix Contact [22]. This solution consists of a module with standard inputs and outputs, which can send and receive information via GSM. Through a mobile application or browser, users can access the information and set up alarms and notifications. The system can be used with any type of machine and can be installed by the user on mostly cases. The cost from a complete version with alarms and notifications is around 600€.

From the previous analysis, for many SMEs companies these solutions are too expensive. Nevertheless, there are in the market companies offering tailored medium-low cost solutions that do not support the migration to different scenarios, scalability, and easy interfacing with the ICT systems. Based on this reality, a new approach for a simple, flexible, and low-cost machine monitoring system was developed with the project name "b-Remote".

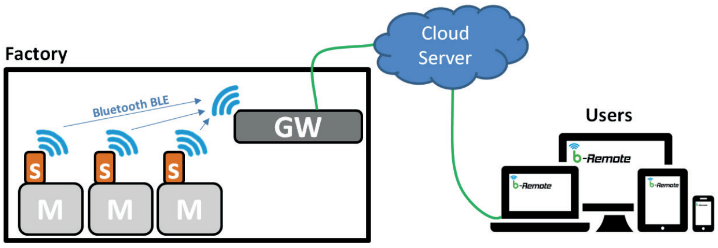
3. PROTOTYPE DEVELOPMENT – THE B-REMOTE

The b-Remote should be a simple and low-cost system with the principal functionality of monitoring the machines status remotely. The architecture of the system is shown in the Figure 2 and follows the steps: 1- the machine's signal is collected from a sensor connected to the relay, contactor or PLC output of the machine; 2- via Bluetooth Low Energy (BLE) the sensor transmits the information to a receiver (gateway), which collects the information from all sensors; 3- the receiver processes and aggregates all the data and sends it to a server on the Internet; 4- the server then collects, processes and stores the data; 5- through a web interface upon a browser, the user can monitor the machines status and stops, and analyse statistics from specific periods.

Solutions / Requirements	MDC Software (Predator Soft.)	MDC-MAX (CIMCO)	Machine Metrics (MachineMetrics)	Leanworx Cloud (Leanworx Tech.)	EIT (Sidel)	TC Mobile (Phoenix Contact)
Accessible from devices with internet access	Yes	Yes	Yes	Yes	NI	Yes
Secure access, defence against attacks	NI	NI	Yes	NI	NI	NI
Machine status information	Yes	Yes	Yes	Yes	Yes	Yes
Easy access to information	Yes	Yes	Yes	Yes	Yes	Yes
Create and export reports. pdf or.csv	Yes	Yes	Yes	NI	Yes	NI
Collect data from any machine	Yes	Yes	Yes	Yes	No	Yes
Access via browser, without any app	No	No	No	Yes	No	No
Different access and use levels	Yes	Yes	Yes	Yes	Yes	NI
Alarms, via SMS and e-mail	Yes	Yes	Yes	Yes	Yes	Yes
IT networks separate from control	Yes	Yes	Yes	NI	No	No

Table 1 – Comparison of the monitoring solutions.

Legend: NI – Not Identified



Legend: S – sensor, M – machine, GW – Gateway, Green Line – Ethernet bidirectional connection (receive-send data)
Figure 2 – Architecture of the system b-Remote (from the authors)

3.1. SYSTEM COMMUNICATION

For the communication, various technologies like GSM and Wi-fi were possibilities. The GSM would be independent from the customer infrastructure. However, would need network coverage and would be potentially costly depending on the number of signals needed. A simpler solution was necessary. The Wi-fi could cover all the areas from a factory. It could enable fast and large data transfer, and as soon as it was established, it could be very independent. The first idea was to use Wi-fi, however, would be necessary to develop code to the sensor and gateway, bringing complexity.

A new solution was searched, simpler and cheaper, and based on the most important information to obtain, "Is the machine running or not?", information that doesn`t require large quantities of data, just a simple signal on/off. The idea was to find a transmitter, to send the signal to a receiver, which will listen to all the transmitters in his range. During the search, the words Bluetooth, beacon and Bluetooth Low Energy appeared. Further research allows concluding that the technology BLE fits perfectly with both sensor and communication requirements. The diversity, adaptability, and low cost of the beacons (transmitters), led to the choice of the BLE.

The BLE was released as an extension of the Bluetooth version 4.0. Developed for applications where energy capacity is limited, and only small amounts of data are required. The purpose of the BLE is to allow a reduced power consumption (maximum 15 mA), keeping the device asleep and activating periodically for data sending. In addition to the adaptability, the reduced energy consumption lowers the cost of the beacons. Another feature of BLE is that the network size is undefined [23, 24].

The BLE devices can communicate in two different modes, advertising and connected. In advertising mode, the BLE device is a transmitter, periodically sending advertisements through the Generic Access Profile (GAP) module. The period to send advertisements can be set from 20 ms up to 10 s (greater power saving) [25]. In this project it was used the advertisement mode because it is only necessary that the receiver (gateway) listen and detects the advertisement from the transmitters (sensors) and through that information, identify the sensor. In the context of this project, it was tested a refresh period between 20 ms to 1s, (configurable by the user) with good results.

The market survey identified a wide range of manufacturers with low-cost BLE devices on the market. The preliminary selection was beacon oriented and the result focused in three main types powered by: Battery, Universal Serial Bus (USB) and Screw-terminals. The battery powered solutions were excluded because it was required a switch on and off signal by the machine. Beacons powered by USB were chosen because of the easy adaptation to different machine signals through the respective intermediate module, and because they are more cost effective. In this project, the beacon used has an antenna to increase the transmission range, although in some applications it is not needed. The choice of beacons as a machine-gateway signal transmitter, determined the use of BLE in sensor-gateway communication.

3.2. SYSTEM SENSOR

The system sensor consists of two parts, the acquisition of the machine signal and the transmission to the gateway. As mentioned above, to the transmission part a BLE beacon was used. To the acquisition of the signal, some possibilities have been studied, considering different signal types and different ways to obtain them. Following, the signal acquisition solutions studied:

- For machines with relays or contactors, if the machine has 24VDC power supply, the signal must be connected to a converter to 5VDC and USB output.
- On machines without relays or contactors, the owner or system user, should be responsible for providing the signal. In these cases, extra hardware and work may be necessary. This solution does not fit the requirements of easy installation and low cost.
- If the machine power supply is between 100 and 240 VAC, the principle is the same, only the converter is different. The solution is an AC/DC converter, like the smartphone charger. It should be used with a female connector, already prepared with terminals for the connection of the machine signal. Most machines have 110 or 220 VAC power supply, which allows this solution, whereby was chosen for our prototype tool.

3.3. GATEWAY

The gateway has the function of receiving the signals emitted by the sensors, the processing of this information and subsequent sending to the server. For its construction, it had to be considered that it needs to be a BLE receiver. The device chosen was a Raspberry Pi 3 Model B, which has integrated Bluetooth 4.1 + BLE and Wi-Fi, as well as a Local Area Network (LAN) port. The storage is by MicroSD card, making it easy to initialize, upgrade or replace in the event of a malfunction. In addition, the cost is in line with the intended for the project.

Developing the gateway, an image was created on the microSD card, having already pre-installed most of the software that was needed. A Python 3 language application was developed to control the BLE module to search for beacon transmissions, processing the results and sending them to the server through HTTP requests. To control the BLE module, the library "pybluez" has been used [26]. The application created is based on the "beacontools" library [27]. Modifications were done to limit the information received only to beacons with a given Universal Unique Identifier (UUID). This way, the reception of signals from other BLE modules in the vicinity was avoided, reducing interference and the possibility of communication congestion. This application starts whenever the operating system starts and thus allows the gateway to function independently, requiring no peripherals such as a monitor, mouse or keyboard.

3.4. WEB INTERFACE

To host a server with database and a website, a hosting was purchased. The server receives the information sent by the gateway and stores in the database (MariaDB). To the user access the database information and later complete some fields, a web page is used. For the server and web page programming, was used the Laravel v5.4 framework and the programming languages PHP, Javascript (JS) + jQuery and HTML + CSS.

Figure 3. b-Remote web page "Main Menu" view

Communication with the gateway is based on HTTP requests for registration in the database and sending the necessary information, such as the beacons to look for.

The system has different types of user permission and the user can be assigned to one or more machines in a company. The information processed and sent to the page is organized according to what it is intended to show to the user. It is also prepared to collect information such as new user registrations, machines and stop justifications.

The web page allows the visualization of the information, the complement of it and an interaction with the server. It consists of five views: Main menu; Machines; Stops; History; and Management.

In the *Main Menu* (Figure 3) it can be seen quickly the status of the machines. There is a notification if any machine has unjustified stops (user defined), as well as a log of the latest events. In the *Machines* view, the user with the necessary permissions, can consult the status of a particular machine. In this view, in addition to the current status, it can be selected a time period and view the key indicators such as the number of stops, unjustified stops, total stop time, most frequent stop, etc. In the *History* view, the solution allows consultation of the detailed record on each machine. As an instance, the stops history list is one of the important information of the system and its data can be edited in case of necessity.

4. TECHNICAL VALIDATION

Upon completion of the first version of the prototype, simulations began. The simulations were performed in two different scenarios, laboratory and industrial.

4.1. SIMULATION IN LABORATORY ENVIRONMENT

The simulations in laboratory environment had two phases:

- The first phase considered 4 configurations to check (see Figure 4). One of the objectives of this simulation was to verify the behaviour of the system indoors, the range and influence of walls and obstacles on transmission. Another objective was to control the gateway ability to operate over

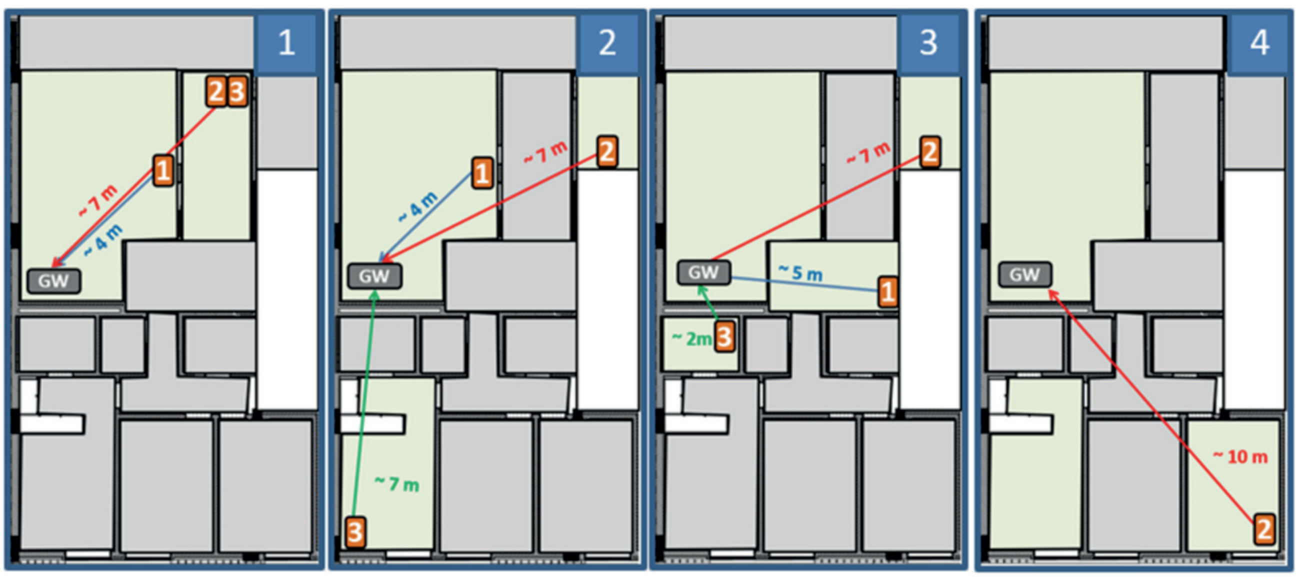


Figure 4. Drawing of beacon distribution on the four configurations

Phase/Simulation Data	1st phase / 1	1st phase / 2	1st phase / 3	1st phase / 4	2nd phase / 1
Test duration (h)	18	18	18	18	1
Nº of beacons	3	3	3	1	1
Max. distance (m)	7	7	7	10	40
Nº of walls for each beacon	0, 1, 1	0, 2, 2	1, 2, 1	0, 4, 0	0
Nº of faults	0	63	0	67	-
Comment	Worked correctly	Many false stops of short duration due to the difficulty to receive the signal of the beacon 3	Worked correctly	Without detection of the signal of the beacon for long periods, short periods of detection	Reception ok until 40m and with intermittences until 65m.

Table 2. Simulations results for the 2 phases

long periods and its ability to make multiple submissions to the server without overloading. To perform this simulation, beacons were distributed by specific house divisions and recorded the transmission during certain periods.

- The second with the gateway inside and the sensor outside. It consisted of checking the range and behaviour in the open field. In this simulation was also verified the possibility of accessing the system through mobile network. A beacon was connected to a powerbank and signal reception was verified via mobile phone.

The results of the first and second simulation phases are presented in the Table 2 and are crucial to define the final configuration of the system for real scenarios. With the configuration one, there was no stop. The simulation lasted 17 hours. With configuration two, there were 63 false stops. Most of these recorded within 53 minutes, where 55 incidents occurred. The cause for these stops is attributed to the location of beacon 3, located at 7 meters and separated by walls and furniture, where a Wi-Fi signal isn't usually available. The solution was to place a gateway closer to beacon 3. In configuration three, the position of beacons 2 and 3 was changed and no stops were recorded. In configuration four only beacon 2 was used to simulate an internal further point. It has been found that there are long periods (hours) without any signal reception and shorter periods where several intermittent detections have occurred which generated 65 false stops in 47 minutes. Such application would require placing the gateway closest to beacon 1.

In the second phase of the simulation, beacon 1 was transported out of the laboratory and signal reception was verified in the open field. It was found that up to about 40 meters it is possible to receive the signal without fail. Up to 40 meters, reception is possible, but with failures.

4.2. SIMULATIONS IN INDUSTRIAL ENVIRONMENT

As the results in laboratory were satisfactory, it was considered that the prototype was fit for factory simulation. The simulation was carried out in a productive environment at the Sopais company (www.sopais.pt), where metal components are produced, to test signal coverage, data integrity and communication device's reliability.

The results obtained for the five industrial simulations carried on are presented in the Table 3. For each simulation it was accounted the total number of stops, the stops with relevance (superior to 25 seconds), and a commentary of each simulation. During the simulations, system tunings were done to avoid the identification of stops without relevance. The results presented in Table 3 shows that progressively the percentage of stops with relevance was increasing until achieve 100% in the last simulation.

4.3. DISCUSSION OF THE MAIN FEATURES OF THE SYSTEM

Industrial control systems represent a system with the ability to control and monitor a production process. According to Putnik et al. [28], the best solution should allow it to be customized to the individual needs of each company. In fact, this was one of the main concerns of our prototype. The Table 4 results shows that b-Remote accomplish the main requirements identified on the Table 1 and aligned with the major solutions presented in the same table. For the rest of the requirements, will be possible to satisfy according to the client needs (different application sceneries) and further development of the solution. Besides this, additional features perceived in the b-Remote are: easy and quick installation; flexible and independent setup from the actual installation; simple and intuitive utilization; remote accessible in real-time; and low cost (around 200€ of pack of four licenses plus 100€/year for cloud service).

5. CONCLUSIONS

The developed system integrates with existing machines in a non-intrusive way. The communication between the different components is performed wirelessly, which makes it modular and low cost. It`s access is flexible through any device with internet access, and the interaction is simple and intuitive. The simulations in laboratory and in industrial environment have technically validated the system. The results demonstrate good range and interference immunity as well as easy installation and utilization. They also attest the possibility of monitoring in real time and remotely through any device connected to the internet.

Simulation / Data	Sim. 1	Sim. 2	Sim. 3	Sim. 4	Sim. 5
Test duration (h)	8	8	8	8	8
Total nº of stops	81	44	32	28	3
Stops with relevance	37 (46%)	13 (30%)	20 (63%)	23 (82%)	3 (100%)
Comment	Stops due to adjustments needs	Stops due to adjustments needs	Stops due to the setup of a new tool	Stops due to the setup of a new tool	Just 3 stops, all planned

Table 3. Results from the industrial environment simulation

Requirements / Solution	Accessible from devices with internet access	Secure access, defence against attacks	Machine status information	Easy access to information	Create and export reports.pdf or.cvs	Collect data from any machine	Access via browser, without any app	Different access and use levels	Alarms via SMS and e-mail	IT networks separate from control
b-Remote	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes

Table 4. Requirement's fulfilment of the b-Remote

The system prototype has some points improvable in the future, such as the gateway hardware that can be changed to a cheaper one like the new ESP32, the website design and new features that were not developed because it is a prototype. It can be expanded to implement and communicate with other systems, collecting more data. There is an opportunity for the study and development of a system integrable with this one, in the area of traceability within the manufacturing space, using the existing gateways, as they are already prepared to communicate with wireless technology.

Despite the improvements that can be done in the future, the proposed solution presents significant competitive attributes compared with the current market offers. Namely, it relies on low cost and easily available technological components, it fully supports an open-source software framework, implements a modular architecture facilitating scalable solutions, and fosters the integration with legacy systems and equipment omnipresent on each SME shopfloor plant. In short, the current solution even though it was developed for a concrete application case in a metalworking industry, it can be replicated in a broad range of similar scenarios on different industrial sectors.

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