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A Review on Human-Centered IoT-Connected Smart Labels for the Industry 4.0

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ABSTRACT One of the challenges of Industry 4.0 is the creation of vertical networks that connect smart production systems with design teams, suppliers, and the front office. To achieve such a vision, information has to be collected from machines and products throughout a smart factory. Smart factories are defined as flexible and fully connected factories that are able to make use of constant streams of data from operations and production systems. In such scenarios, the arguably most popular way for identifying and tracking objects is by adding labels or tags, which have evolved remarkably over the last years: from pure hand-written labels to barcodes, QR codes, and RFID tags. The latest trend in this evolution is smart labels which are not only mere identifiers with some kind of internal storage, but also sophisticated context-aware tags with embedded modules that make use of wireless communications, energy efficient displays, and sensors. Therefore, smart labels go beyond identification and are able to detect and react to the surrounding environment. Moreover, when the industrial Internet of Things paradigm is applied to smart labels attached to objects, they can be identified remotely and discovered by other Industry 4.0 systems, what allows such systems to react in the presence of smart labels, thus triggering specific events or performing a number of actions on them. The amount of possible interactions is endless and creates unprecedented industrial scenarios, where items can talk to each other and with tools, machines, remote computers, or workers. This paper, after reviewing the basics of Industry 4.0 and smart labels, details the latest technologies used by them, their applications, the most relevant academic and commercial implementations, and their internal architecture and design requirements, providing researchers with the necessary foundations for developing the next generation of Industry 4.0 human-centered smart label applications.

INDEX TERMS Smart labels, human-computer interface, smart objects, Industry 4.0, human-centered design, traceability, tracking, cyber-physical system, IoT, IIoT.

I. INTRODUCTION

In traditional factories, the communication between a product and a worker, and among the different operators that act on the value chain, is usually slow and inefficient. For instance, when a designer or engineer gives instructions to workshop workers on how to assembly a new product, it is really difficult to update such instructions dynamically as errors are detected or as feedback is received from operators. Thus, the usual solution consists in carrying out direct communications between the designers/engineers and the workshop workers.

Another common problem in traditional factories is the lack of a whole traceability of the product. In many cases operators do not know exactly in which manufacturing stage the product is or where it is physically located. This lack of traceability derives into inefficiencies and the absence of knowledge on which tasks are actually being performed or have been performed on the factory at specific time instants. In fact, it is also common not to know in real time which products are ready to ship or where they are.

Human-centered design [1] is an approach to system design and development that aims to make interactive systems more usable and useful by focusing on their use by operators and their requirements within a collaborative industrial environment. This approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance.

Human-centered smart systems [2]–[6], together with the design principles of the Industry 4.0 paradigm [7], suggest different alternatives to tackle the previously mentioned issues, requiring the connection among all the actors of the manufacturing chain, from semi-finished products, to workstations, as well as machines and workers. Therefore, if a factory wants to become ''smart'' (i.e., be able to take the most of the data collected from operations and production systems), it needs to provide real-time connectivity to the products and items.

There are mainly two solutions for providing connectivity to objects: either the objects already embed some kind of processing unit or such objects are attached to hardware elements whose software makes objects ''smart''. The former is usually over-killing in many situations (e.g., it is maybe not reasonable to make smart every bolt of an assembly), so smart labels are glued or attached to objects or sets of objects.

Labels, which are designed to be used directly by operators (by non-engineers in particular), have been used through history for identifying items unequivocally, first manually and then automatically thanks to the use of computers and diverse identification technologies. Such an identification is performed by assigning to the item a product code that is known as Global Trade Item Number (GTIN) [8], although some retailers prefer to use EAN (European Article Number) or UPC (Universal Product Code) barcode symbology. GTIN and EAN/UPC codes are still widely used, but traditional paper and plastic labels have evolved a lot in the last years: first from simple barcodes to Radio Frequency IDentification (RFID) tags, and then to sophisticated smart labels that embed modules that provide wireless communications, energy efficient displays, sensors and actuators. Smart label technology is so promising that is expected to grow significantly in the next years together with Electronic Shelf Labels (ESL) [9], creating a market of US $16.12 bn in 2025 [10].

This article reviews the main characteristics of smart labels, their internal structure, the communication architecture and the latest technologies that they can make use of. Moreover, it details the relationship of smart labels with the Industry 4.0 paradigm, indicating possible applications and analyzing the requirements for the smart label based systems of the Industry 4.0 factory.

The following are the main contributions of the article, which, as of writing, have not been found together in the literature:

- The article reviews the main characteristics of the most recent smart label systems for industrial applications.
- It provides a thorough comparison on the latest communication technologies for creating smart label systems.
- This article also identifies and discusses different use cases where smart label can be useful for Industry 4.0.
- It proposes a novel design of a smart label system following the principles of the Industry 4.0. Furthermore, it provides an overview of the key challenges, and the relationships among smart labels, IoT and other emerging technologies.

The remainder of this paper is organized as follows. Section II reviews the main Industry 4.0 concepts, challenges and the most relevant technologies involved. Section III compares the features of traditional approaches of labeling technologies with smart labels. Next, it summarizes the main commercial and academic smart label developments. Section IV proposes the design of a smart label system following the requirements of the Industry 4.0. Section V identifies the main challenges for a massive deployment of smart labels. Finally, Section VI is devoted to the conclusions.

II. ABOUT INDUSTRY 4.0

A. BASICS

Industry 4.0 refers to the next stage in the evolution on the organization and control of manufacturing processes. The term Industry 4.0 actually comes from a project funded by the German government [11], which is said to be first made public during the 2011 Hannover Fair [12]. The term was received with enthusiasm by the worldwide industry [13] and overlaps in part with other paradigms like Industrial Internet of Things (IIoT) [14] and with other initiatives such as Made in China 2025 [15]. In addition, Industry 4.0 is directly related to the deployment of smart factories [16], which are conceived to manage more efficiently their resources and to incorporate enough flexibility to adapt to the production needs. Such a necessity for flexibility is associated with the fact that clients are increasingly demanding product customization [17], what impacts development and manufacturing at different stages (e.g., design, ordering, development, production, sale, after-sale or recycling).

One of the principles of Industry 4.0 is to collect as much information as possible in real time from all the different parts of the value chain. In addition, data collection should be as efficient, fast and flexible as possible, what involves collecting and analyzing data with computerized machines that also help to decrease production costs and to increase quality. For achieving such improvements, IIoT systems and Cyber-Physical Systems (CPSs) are essential, since they allow for collecting, processing and storing the data obtained on real-world objects. Moreover, such systems are able to locate and track items [18]–[20] and to exchange data among the different workstations and not only inside the factory, but also with suppliers, clients and the front office (i.e., the company's decision making officers).

By adding intelligence to machines, tools, storage areas or raw materials of a production chain, it is possible

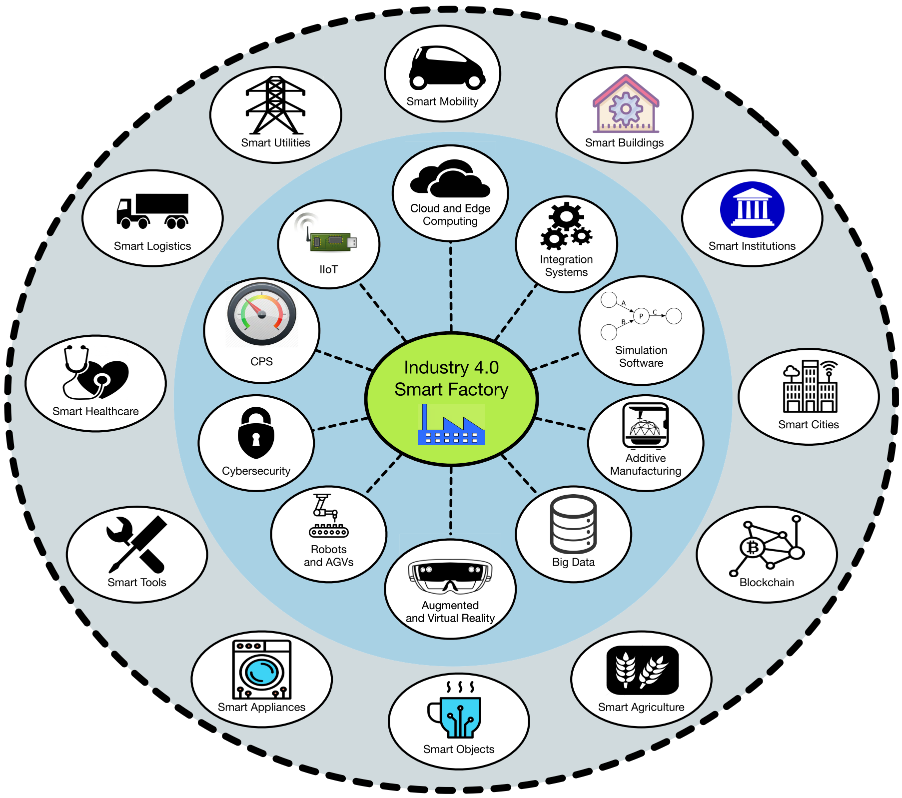

FIGURE 1. Industry 4.0 technologies and related fields.

to adapt the factory to changes, providing flexibility to face industrial and client requirements. Furthermore, such a flexibility enables manufacturing highly customized products and adapting to the actual demand, avoiding the storage of too much stock or its scarcity.

To achieve all the previous benefits, the Industry 4.0 paradigm proposes the use of different technologies. Some of them have been studied for a long time [21], [22], but they are still not mature for a massive industrial deployment, like Augmented Reality (AR), [23], [24]. Nonetheless, what makes such technologies disruptive is the fact that Industry 4.0 devices are able to communicate among them autonomously, allowing them to coordinate with each other and with other remote systems on the Internet.

B. MAIN CHALLENGES

Industry 4.0 faces four main challenges for its deployment [25]:

- The creation of networks to integrate smart production systems vertically. Thus, data are transmitted automatically from plant systems to other important pieces of the value chain (e.g., design, lean manufacturing, logistics, sales services).
- The horizontal integration of companies (i.e., manufacturers, providers) and clients to foster cooperation. This kind of integration allows for creating fast and flexible networks that provide decreased response times. In the case of the integration of clients with companies, it will be greatly enhanced through the use of IoT devices and social networks. In addition, technologies like blockchain [26] or Directed Acyclic Graph (DAG) [27] will provide access to all the information in a decentralized way to the different collaborators. Obviously, with such a dependence on networks, cybersecurity will be essential, specially when protecting critical infrastructures [28], [29].
- The integration of design and engineering throughout the value chain. Real-time data collection allows designers and engineers to react fast, so the optimization and customization flow can be performed continuously.
- The introduction of new technologies. Skilled workers will have to interact and also be trained to use CPSs, what means that traditional human-machine interaction will change remarkably and that companies will have to adapt to the use of new technologies.

C. MAIN INDUSTRY 4.0 TECHNOLOGIES

The implementation of the Industry 4.0 principles requires the integration of the technologies described in the next subsections and illustrated in Figure 1. In such Figure some of the areas that Industry 4.0 will have to communicate with in future scenarios are also included, like smart healthcare, smart utilities or smart logistics.

1) IIoT
The term IIoT refers to the use of Internet of Things (IoT) technologies [30]–[33] in industrial environments. Therefore, it implies the massive deployment of industrial sensors, actuators and machines with remote sensing/actuation capabilities [34]–[36].

2) CPS
A CPS can be defined as a system with processing, storing and communication capabilities that is able to control one or more physical processes. Such systems are usually interconnected with each other or through the Internet, what decentralizes data analysis and decision-making, enabling real-time responses [37]–[39].

3) VERTICAL AND HORIZONTAL INTEGRATION SYSTEMS
As it was mentioned in Section II-B, horizontal and vertical integration are key for Industry 4.0 in order to automate data transmission in smart factories and to communicate with providers and clients. Therefore, software like Manufacturing Execution System (MES), Product Life-cycle Management (PLM), Enterprise Resource Planning (ERP) and IoT platforms will have to evolve to provide the required integration level.

4) ADDITIVE MANUFACTURING (3D PRINTING)
The flexibility and customization brought by additive manufacturing are essential in the Industry 4.0 paradigm. Ideally, such characteristics should be provided without raising the price of the product and should not depend on the fact that the manufactured products are identical or different. Moreover, additive manufacturing will make it easier to produce low-volume batches or prototypes, which, traditionally, have been expensive. Furthermore, decentralized additive manufacturing will reduce delivering times and will enable stock management optimization.

5) BIG DATA AND DATA ANALYTICS
Companies usually store a lot of data related to industrial and logistic processes and systems, services (e.g., sales, after-sales) or data traffic (logs of routers and computers). The huge amount of generated data is really valuable, but they cannot be processed manually, so Big Data techniques become useful. Moreover, data analytics helps when processing the information, being able to predict future problems or the necessity for certain resources.

6) CYBERSECURITY
Connectivity is essential in Industry 4.0 applications, so it is required to protect industrial critical systems and manufacturing lines from cyber-attacks, whose impact has grown remarkably in the last years [40]. Therefore, it is key to provide secure and reliable communications, authentication systems and preserve data privacy in order to avoid attacks [41]–[44].

7) CLOUD AND EDGE COMPUTING
Many companies are already deploying applications on cloud computing systems, which are fostered by Industry 4.0 in part because they ease the collaboration with third-parties. Nonetheless, note that traditional cloud-based systems have certain limitations [45], as the cloud is considered a point of failure: when maintenance, software problems or attacks occur, the whole system is blocked. Moreover, it is important to emphasize that, if the amount of IoT-connected devices keeps on growing at the same rate [46], the amount of communications to be handled will increase remarkably and, therefore, the cloud may constitute a bottleneck. Due to this issue, other alternative architectures based on edge computing have been proposed, like fog computing [47] or cloudlets [48], which enable offloading part of the processing from the cloud to the edge of the network, also decreasing latency response [24], [41].

8) SIMULATION SOFTWARE
The collected information can be processed in order to model the behavior of machines, products and workers of certain industrial processes. Such an information can be fed into software that enables simulating future scenarios in order to determine necessities, predict problems, reduce configuration costs and improve quality. This kind of software is also related to the concept of Digital Twin [49], which represents the actual situation on a real-world factory through visual interfaces, what allows for remote monitoring and supervising operations.

9) AUTONOMOUS ROBOTS AND VEHICLES
The next generation of robots that will be used in Industry 4.0 applications includes cobots [50], industrial robots [51] and Autonomous Ground Vehicles (AGVs) [52], which can be interconnected and work in a collaborative way. Cobots help human operators in different tasks, while robots can perform certain specific tasks, like searching items or transporting tools in an autonomous way. Regarding AGVs, they are mainly targeted at logistics and transport in industrial environments, existing AGVs for mining [53], material handling [54] or for automating industrial vehicles [55].

10) AUGMENTED AND VIRTUAL REALITY
AR is a technology that makes use of an electronic device to view, directly or indirectly, a real-world physical environment that is combined with virtual elements. In the case of Virtual Reality (VR), both the environment and the elements are virtual. AR and VR have progressed a great deal in the last years and they have proven to be useful in different stages of an industrial process, like design [56], [57], manufacturing [58], [59] or maintenance [60], [61]. In fact, it has been demonstrated that technologies like AR can help operators to avoid mistakes in assembly tasks and increase productivity [62].

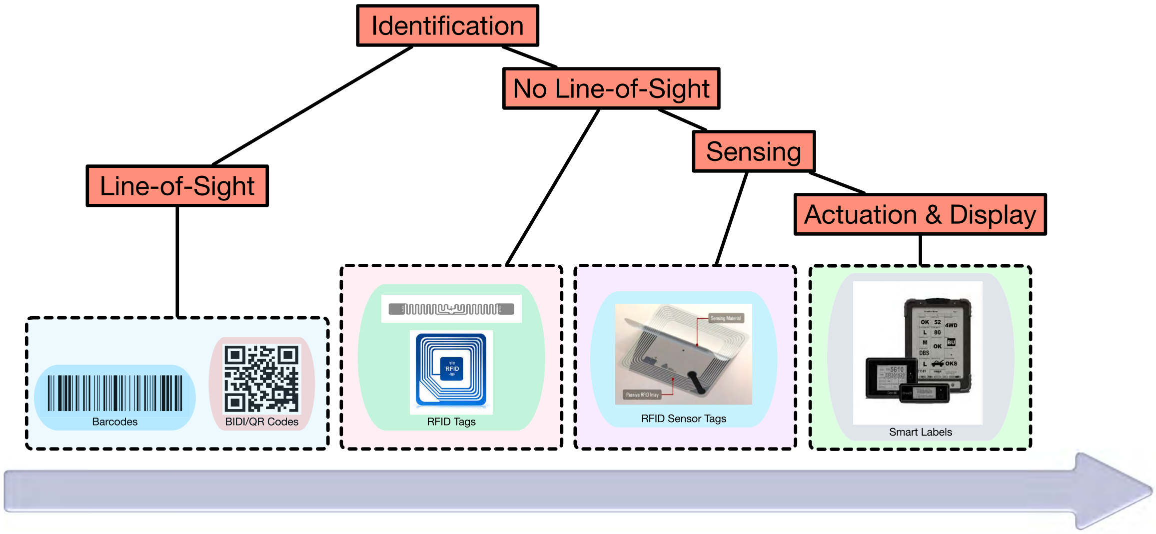

FIGURE 2. **Industrial labeling technology evolution.**

III. SMART LABELING FOR INDUSTRY 4.0

A. TRADITIONAL LABELING

There are several labeling technologies that can be used for the automatic identification of industrial products. The most basic is barcodes, which are basically a visual representation of the GTIN codes previously mentioned in Section I. Barcodes require Line-of-Sight (LoS) in order to read them correctly with barcode readers. In addition, they require a relative short reading distance (up to a few tens of centimeters). Nonetheless, they have been very useful in many industrial applications and have increased item identification speed remarkably respect to traditional manual identification procedures. Moreover, barcodes are really cheap and only require barcode generation software and a printer to start labeling objects. Although in the automatic identification scenario depicted by Industry 4.0 barcodes might seem to be unnecessary, they still can be useful in certain situations where reduced costs, short reading distances or very specific reading locations exist in an industrial scenario.

The evolution of barcodes are bidimensional codes (known as Bidimensional (BIDI) or Quick Response (QR) codes), which originated in Japan in 1994 in order to code Kanji and Kana characters. Thus, in contrast to barcodes, QR codes are able to store certain data (usually more than 1,800 characters), although their processing is more complex. Nonetheless, readings can be carried out with a smartphone camera, what reduces the need for special equipment. QR code reading distance depends on the size of the code: as a rule of thumb, it is usually considered that the scanning distance is roughly ten times the diagonal of the QR code.

Bar and QR codes are usually applied in inventory applications, for tracking parts or in administrative procedures, but their reading distance is limited by the need for line-of-sight, they do not allow for interacting with items, and, obviously, they are not able to report actively on the state of the product they are attached to. Due in part to such limitations, traditional labels evolved towards RFID technology [63], which allows for reading an identification number at certain distance (from several centimeters to meters) and, in some cases, some embedded information. However, the concept behind RFID tags, although valid for many industrial situations, is similar to traditional labels: the tag is just a mere data container or provides a link to the required information that, since it is stored digitally, it can be altered dynamically under some circumstances (i.e., when tags are in the field of a reader or by modifying a remote database). Nonetheless, most current commercial RFID tags do not collect data from sensors and do not allow human interaction (except for very specific models, like Omni-ID Power 60 and 65 tags [64]).

Figure 2 shows the evolution of labeling technologies until the arrival of smart labels.

B. LIMITATIONS OF TRADITIONAL LABELING

As it has been previously mentioned, labeling in factories has evolved remarkably in the last years. Most companies still use cheap paper or plastic labels that contain pure text, a barcode or a QR code. Although inexpensive, such kinds of labels have to be updated manually, the displayed information is static (although they can be linked to a remote database), they cannot be used for receiving inputs from workers or sensors, they cannot be used for remote dynamic positioning (in most cases workers or robots read them manually, so their position is linked to the reading place) and they have to be removed and thrown away when it is considered that they are no longer valid for the item (in fact, it is usual to place a specific label only for a specific process or subgroup of processes during the manufacturing stage).

Three practical examples on the Industry 4.0 value chain can be given in order to emphasize the limitations of traditional labeling:

- In an Industry 4.0 smart factory (i.e., a factory that is flexible and fully connected, being able to make use of constant streams of data from operations and production systems), most manufacturing tasks will be performed automatically, but the tasks to be performed by humans require some kind of documentation [18]. Such a documentation is usually attached to the product, either printed on paper or it is accessible in a digital format through a device used by a worker (e.g., a computer, tablet or smart phone) by reading the label. However, the fastest approach would be to indicate dynamically the tasks to be performed (e.g., the manufacturing procedure, the assembly process or the quality requirements) and their characteristics (e.g., priority, deadline, next manufacturing stage) on the label attached to the product, without requiring further interaction.
- In retail, prices may fluctuate dynamically in real time through the day. However, traditional labels cannot show more than the printed prices. Therefore, more and more retailers started in the last years to use simple smart labels with digital displays to indicate prices to consumers, which can be updated dynamically, automatically and remotely.
- In smart factories or in logistics, many product management tasks are already performed through some kind of connected software, but the labels are still prepared and printed manually, what slows down certain processes.

C. SMART LABELS

In order to optimize the industrial processes carried out in an Industry 4.0 smart factory and to harness some of the technologies described later in Section IV-D, it is necessary to make use of advanced labeling systems to make products "smarter".

This intelligent interaction can be performed in two different ways. The first one consists in interacting directly with the products/parts if they embed the required hardware/software. However, the whole hardware/software is usually not operative until the latest assembly stages, so it is necessary to take a second approach: to add temporary external hardware/software through an intelligent smart label or tag. Such a second approach transforms mere items into smart ones, it is more appropriate during the manufacturing of the product and, in some cases, it can be used after the product has been sold.

The most relevant alternative that emerged due to the limitations mentioned in Section III-B, were electronic labels, which pack in a small footprint a cheap display, a processing unit and a wireless transceiver. Such labels are known as "smart labels" and enable an autonomous operation that requires no human intervention in most scenarios. This autonomy is essential in the Industry 4.0 smart factory, where traditional labels are not appropriate due to the expected automated recollection of data and coordination with other systems. Thus, a new generation of labels is progressively being deployed in the most modern factories. Such labels not only show dynamic information, but include modules with e-ink paper displays that show changing data after receiving them through wireless transceivers from remote cloud or edge computing systems. In addition, smart labels can embed sensors and actuators, which allows for collecting really useful data on processes and that provides a way for the workers to interact with the system without needing external equipment (e.g., tablets, smartphones, PDAs).

Moreover, when the principles of IIoT are applied on objects attached to smart labels, they can be identified remotely and discovered by other systems, what enables them to react to their presence, triggering specific events or performing a number of actions on them. The amount of possible interactions is endless and provides unprecedented industrial scenarios where objects can talk to other objects, machines, remote computers or workers.

Therefore, a smart factory manager can send information to smart labels through wireless communication channels from a remote location and receive data from such labels. These operations are carried out from a central intelligent system, which is able to manage tens of thousands of smart labels simultaneously. This implies that, because human beings do not need to check, print or replace paper or plastic labels, operational costs can be reduced and many human errors can be avoided.

In order to consider a labeling system as smart label-based, it should include the following features:

- Smart labels should provide information on the state of the products they are attached to by using the information collected from sensors, actuators or from surrounding objects/systems.
- An Industry 4.0 smart label should replace the need for printed instructions. Therefore, it should be able to indicate the tasks to be performed on a product at a certain stage. Obviously, the information on the tasks should be updated periodically, as the product travels through the manufacturing chain or depending on the tools and machines available at certain time instants. In addition, the label may show operators the features that the product should have after being processed.
- After a product leaves one processing stage, the system should be able to detect such an event, which should be reflected ideally both on a central traceability storage and on the smart label itself.
- A smart label should also provide communication interfaces to the operator (i.e., actuators). For instance, a simple button (either hardware or software, inside a touch-sensitive display) is enough for indicating that the product has been processed at a specific stage and that the quality control supervision can be performed. In the same way, incidents during manufacturing can be transmitted directly to designers in order to correct engineering errors fast.
- A smart label, ideally, should use technology that eases its positioning, both indoors and outdoors. Positioning is key when triggering certain events in smart factories.

TABLE 1. Comparison of the features of Omni-ID's view smart labels.

Smart Label	Processing Unit	Sensors	Actuators	Communications Technology	Identification Subsystem	Display	Battery	Management	Size (mm)	Weight (g)	Ruggedness	Reading Range	Memory	Price
Omni-ID View 3	Unknown (MonzaX-2K Dura for passive RFID)	Accelerometer	Push button, configurable led for alerts, one GPIO pin for actuating on other devices.	Active 433 MHz RFID (Proprietary protocol).	Active 433 MHz RFID Passive UHF (860-930 MHz) EPC Gen2 RFID.	3" e-ink display	Replaceable lithium batteries. Expected life of 3 years.	It requires to deploy a network of 433 MHz Link Gateways that communicate with a central server. ProVIEW software for rewriting, location and real-time monitoring.	146.5 x 50 x 14.1	99	It withstands water splashes, but they are not water-proof. Recommended for operating between 0°C and 40°C. It withstands 4' drops to concrete.	Passive RFID tag: 3 m for writing and 5 m for reading (on or off metal). Active RFID: 80 m on metal, 100 m off metal.	It includes flash memory for storing up to 16 pages.	US $65
Omni-ID View 4						4" e-ink display	Replaceable Lithium batteries. Expected life of 5 years.		148.5 x 102.5 x 13.9	197				US $95
Omni-ID View 10		N/A	Five configurable tactile buttons with leds.	IEEE 802.11b/g (2.45 GHz) Positioning performed through infrared beacons.	EPC Gen 2 UHF RFID (866 to 928 MHz).	10.2" e-ink display (160 dpi)	Full recharge in under 5 hours (Non-contact recharge).	ProVIEW software for rewriting, location and real-time monitoring.	263 x 205 x 13	680	Recommended for operating between 0°C and 50°C. It withstands 4' drops to concrete.	IEEE 802.11b/g range: 50 m (typical).	25 MB (i.e., 162 to 255 pages, depending on compression ratio).	US $490

In most cases it is not necessary to provide millimeter-accuracy, but point to a reduced area where the item is located [20].

- All the information on the smart labels should be stored either in centralized systems (e.g., servers, a cloud or a server farm), in decentralized systems (e.g., fog computing gateways or cloudlets), or distributed among peers (e.g., in a blockchain).
- The information collected on the smart labels should be processed in real time, showing in a CPS the state of the products, warnings, events and all the relevant information for the factory operation. Moreover, the digital twin concept can be applied to get a clear picture of what is happening in every specific area of the smart factory.
- It should be provided some kind of communication mechanism with providers, which should be contacted, for instance, when certain materials run low and it is expected more incoming work that would require them.

D. COMMERCIAL AND ACADEMIC SMART LABELS AND DEVELOPMENTS

In the last years there has been a lot of research on sensing RFID applications (for instance, for measuring temperature [65], acceleration [66], light [67], relative humidity [68], sound [69] and even physiological parameters [70]), but not many specific smart label based systems have been described in the literature. It must be emphasized that the concept of smart label proposed in this article should include the subsystems described later in Section IV-B and, although many of them may be present, it seems that the lack of an embedded hardware display rules out many systems. Nonetheless, there are several really interesting smart label systems that can be used in Industry 4.0 applications.

For instance, View smart labels [71] are probably the most sophisticated on the market. They have been developed by Omni-ID [72] and are composed by a central software system that manages a number of smart labels. There are currently three models: View 3, 4 and 10. View 3 and 4 labels include a 3 or 4-inch e-ink display and flash memory storage. Such labels can communicate using active RFID that operates at 433 MHz, but also embed a passive 900 MHz UHF EPC Gen2 RFID tag. In the case of View 10 smart labels, they feature a 10.2-inch screen, a WiFi transceiver, a UHF EPC Gen2 RFID tag and infrared receiver for beacon-based positioning. The specific features of the different models of View smart labels is shown in Table 1.

The arguably most popular smart labels are the ones known as Electronic Shelf Labels (ESLs) [73]–[81], which are used in supermarkets for indicating prices. For example, a novel IoT electronic shelf label for retail markets is presented in [82]. In such a paper the author details a smart labeling system that works in combination with an application that links every label with a specific smartphone app, what allows for providing content to the label. Although the design of an ESL has remained basically the same in the last years [83], some researchers suggested improvements like adding energy harvesting capabilities [84], enhancing the communications protocols [85], replacing the ESL radio transceiver with a light communications module [86]–[88], improving energy efficiency with WSN technology [89] or creating a framework to manage heterogeneous ESLs [90].

Smart labels can also be used for providing intelligence to everyday objects. For instance, Nokia led a project [91] that proposed the use of passive RFID smart labels with large non-volatile memories that would be placed in public spaces. Users would communicate with the labels through their smartphones, thus being able to interact with the environment. Note that this approach differs from traditional RFID systems, where data are stored in remote databases. In addition, since smart labels do not exchange data with each other, the users are the ones that transport the information from one place to another, avoiding the need for keeping objects connected continuously to an IoT network. This approach can be useful in factory locations where there is no network access, but it is required to obtain or write information on certain items.

A summary of the most relevant commercial and academic smart labels and advanced smart tags is presented in Table 2.

IV. DESIGNING A SMART LABEL SYSTEM

A. INDUSTRY 4.0 REQUIREMENTS

Smart labels can be used in many industrial scenarios with very different requirements. However, there is certain functionality that is common for most Industry 4.0 smart label based applications related to modern manufacturing lines. Thus, smart labels should:

- Identify an item at a certain time instant. Nonetheless, smart labels should be reusable, so the same label could be attached to different items through time.
- Show information on the characteristics of the item that are relevant to the processing stage where it is located.
- Be able to receive and send information through a wireless transceiver.
- Provide basic actuators, like push-buttons or small joysticks, to allow workers to interact with the smart label.
- Ease the tracking and positioning of the products.
- Capture, show and be able to transmit the data collected by sensors. However, note that some of such data may only be needed locally (for instance, an accelerometer may be used to activate wireless communications only when the smart label is moving), so not all the collected information should be forwarded to the cloud.

Regarding the smart label management system, it should include the following main features:

- It should be able to exchange information with the smart labels scattered throughout a factory. This requirement implies the necessity of an infrastructure to collect or send data.
- It should enable performing remote management operations on the smart labels (e.g., associate or de-associate the smart label with a product).
- It should show in a user-friendly way the information received from the smart labels and give a global overview of the status of the different parts of a plant.
- It should collect the requests from the smart labels, which may be triggered by their position or by the commands sent after activating an actuator.
- From the data collected, it may make use of Big Data or Data Analytics techniques to perform predictive maintenance tasks, detect possible production bottlenecks or warn on different imminent conflictive events.

B. SMART LABEL SUBSYSTEMS

Figure 3 shows the internal architecture of a smart label. As it can be observed, it is composed by the following subsystems:

1) **Sensing and Actuation Subsystem**. It is in charge of capturing the environmental information (e.g., temperature, humidity, noise), the parameters that directly impact the smart label (e.g., movement or pressure), and the activation of the actuators.
2) **Communications Subsystem**. It allows for exchanging information between the smart label and the Management Subsystem.
3) **Control Subsystem**. It is responsible for managing both the information that comes from the Communications Subsystem and the Sensing and Actuation Subsystem. In addition, due to its control over the other subsystems, it is essential for implementing the energy efficiency policy.
4) **Identification Subsystem**. Its aim is to provide and guarantee that the smart label is identified correctly.
5) **Display Subsystem**. It shows to the plant operators the information received by the smart label through embedded hardware displays. It is managed directly by the Control Subsystem.
6) **Power Subsystem**. It is responsible for powering the smart labels.
7) **Management Subsystem**. It is structured into three layers:
    - Management Layer: it collects and processes the information received from the Sensing and Actuation Subsystem, and displays it in a friendly way to the users.
    - Information Provider Layer: it sends the appropriate information at the right time instants to the smart labels. Such transmissions can be triggered automatically by events or they may be sent manually by the administrator of the Management Subsystem.
    - Storage Layer: it stores all the relevant data and events gathered and generated by the smart label system.

Note that a smart label is, like other IoT and IIoT devices, a resource-constrained system that has to be cheap, small and energy efficient, since it is powered by batteries.

Smart labels are physically attached or placed near the target objects so operators can recognize which tags belong to which products. Therefore, there is an association that maps logically a smart label with an item. Although paper or plastic labels do not explicitly define such a logic association, smart labels maintain the association by using special operations to associate/de-associate, update and delete the relationship.

C. COMMUNICATIONS ARCHITECTURE

The development of an architecture for supporting the smart label system is a challenge due to its specific requirements. For instance, to save energy, smart labels are asleep most of the time and wake up periodically in order to determine if there is pending work for them. This behavior implies that there has to be a trade-off between energy savings and response latency.

Figure 4 shows the traditional communications architecture of a smart labeling system. It is basically a hierarchical system controlled by the management software (at the top of the architecture) that exchanges data with different

TABLE 2. Main characteristics of the most relevant commercial and academic smart labels and advanced smart tags.

Label	Communications	Sensors	Actuators	Controller	Display	Other Features	Applications
Organic Electronic Label [65]	RFID	Organic temperature sensor	–	Hybrid CMOS	Organic thin-film transistor (OTFT)	Does not need battery, WORM memory	Temperature-tracking of goods during the logistic transportation
RFID Threshold Accelerometer [66]	ATA5570 Passive RFID tag	Latching bistable accelerometer	–	Microcontroller	-	Reading range 3 cm	Shipping industry
Chipless RFID Tag for Light Sensing [67]	UHF RFID	Passive light sensor	-	CMOS	–	–	Maintenance-free indoor light intensity monitoring, plant growth in green house environment, condition monitoring of photosynthesis process
Smart label [68]	RFID	Humidity, temperature, light intensity sensors	-	CMOS	-	Low-cost and low-power integrated microsystem	Tracking food information and monitoring its preservation conditions
Indoor acoustic localization platform [69]	RFID	UHF EPC Gen2 RFID reader and an array of ultrasonic beacons, custom passive tag (WISP) using ToA	-	Microcontroller	–	1.5 cm of accuracy, latency of 0.7 s (mean), 2.2 m range	Inventory, asset tracking and robotic-manipulation of tagged items
S-tag [70]	UHF RFID	Generic sensors	–	Low frequency CMOS controller	-	Batteries, powered by the RFID reader in the future	Healthcare
View 10 [71]	RFID, WiFi transceiver, infrared receiver for beacon-based positioning	–	5 tactile buttons with leds	–	10.2 inch e-ink display and flash memory storage	Lithium batteries, non-contact recharge	Work instructions in manufacturing & healthcare, repair manuals for maintenance, manifests and pick lists for logistics, reports and forms for quality control, productivity graphs & reports for improving operations
Pick to light systems NW series (ESL) [73]	Ai-Net wireless protocol	–	7 color high-intensity LEDs, confirming buttons	–	E-ink panel capable of representing images, 2D codes	Rechargeable batteries	Put-to-light sorting system for warehouses or production centers
Pricer SmartTAG HD (ESL) [74], [79]	Bidirectional infrared	–	–	–	E-ink display	Replaceable battery	Product and marketing promotion information (QR codes, graphics, branding etc.) is combined with active price strategy and automation.
Arkscan ESL Freezer 2.13 Display [75]	WiFi	–	3 color LED light	–	2.13-inch e-ink display with LED flashing light	-	Frozen products
Eastsun Cold chain logistics monitoring smart labels [76]	–	Temperature, humidity, vehicle speed, cargo status	–	–	Visual display data	Zero-power display	Logistics and warehousing industry
Displaydata Aura 29 BLE (ESL) [77]	BLE for customer interaction	Temperature	–	–	Black on ‘paper-white’	–	Retail pricing
Ses-imagotag S-tag+4 (ESL) [78]	Radio Force X4 (RFX4)	–	Dynamic blinking	–	TN-LCD segment	Battery lifetime (room temperature) 5 years (2 updates per day), Battery 1 x 3 V 600 mAh	Shelf tagging and price automation
Hanshow STELLAR EPD-XXXL@ [80]	NFC technology upon request	–	3 color led flash reminding goods inventory information, promotions, self life	–	7.5" e-ink bi-stable graphic, black/white/red	Battery: 6× CR2450, 3300 mAh, battery lifetime 5 years (4 updates per day)	Price management, intelligent fresh food section, shelf management, precision marketing
Else SmartTAG HD 200, Extra-large Graphic Labels [81]	Wireless low power flash capacity and NFC	–	–	–	Fully graphic, e-ink display	Up to 7 years battery life, easy cassette change out	Multiple pages for merchandising and inventory information
Smart label platform towards IoT [82]	IEEE 802.15.4, RFID	-	–	–	E-ink display	Duty-cycling to reduce power consumption	Retail market, smartphone content such as SMS, weather forecasting, schedules, blogs, twitter, or Facebook virtually associated with smart labels
ESL Based on Electronic Paper Display [83]	–	Temperature sensor	-	MSP430F149 as microprocessor and AVT6202 as e-paper driver	E-ink display	Low-power consumption	Product management and pricing
Energy harvesting framework for ESLs [84]	Wired or wireless communication	–	–	Central controller	E-ink display	Indoor solar cell-powered label nodes	Wireless green-powered sensor networks, large-scale testbed 12,000 nodes request a price update every five minutes and achieve a minimum individual success rate of 80 %.
ELS based on WSN [85]	CC2500 module for the communications between Router and Label, nRF905 module for the communications between Sink and Router	–	–	MSP430F149	e-ink/bistable LED display	Ultra-low-power, 2xButton batteries, 3-5 years	Real-time price update
ESL system based on public illuminating network [86]	Light communications module	Semiconductor color sensor	White Light-Emitting Diodes (WLED)	–	LCD screen	Built-in solar cell	Real time wireless updating of shelf-edge information in hypermarkets, only the labels belonging to the same cluster get updated during the same period of time.
ESL with Visible Light Communications (VLC) [87]	VLC downlink and infrared uplink with the central controlling unit, information exchange with local management via PLC	–	LEDs	Arduino Uno, 8-bit ATmega 328, 16 MHz	E-ink display	Photovoltaic cell, energy harvesting unit	Profiling customer habits and preferences through the customer’s smartphone, consumer interaction and social network integration
ESL with a Visible Light IDentification (VLID) link [88]	ZigBee, VLID	PDA36A Photodiode	LED light	–	LCD display shutter	–	Retail dynamic pricing
ESL [89]	ZigBee	–	LED lights	CC2430 SoC	LCD used E-ink display (SIC05112)	Hardware and software low-power design	Shelf management
RF memory tags [91]	Passive RFID	–	–	–	–	Energy harvesting	Tourist services, social networking
Diebold Nixdorf ESL [92]	NFC-N and NFC-L option	–	–	–	E-ink display with B/W or B/W/R pixels or TFT display with B/W pixels for freezer use	Battery: CR 2450 3V, 600 mAh, service lifetime: 5 years (two updates per day)	Price labeling system based on radio-controlled electronic labels

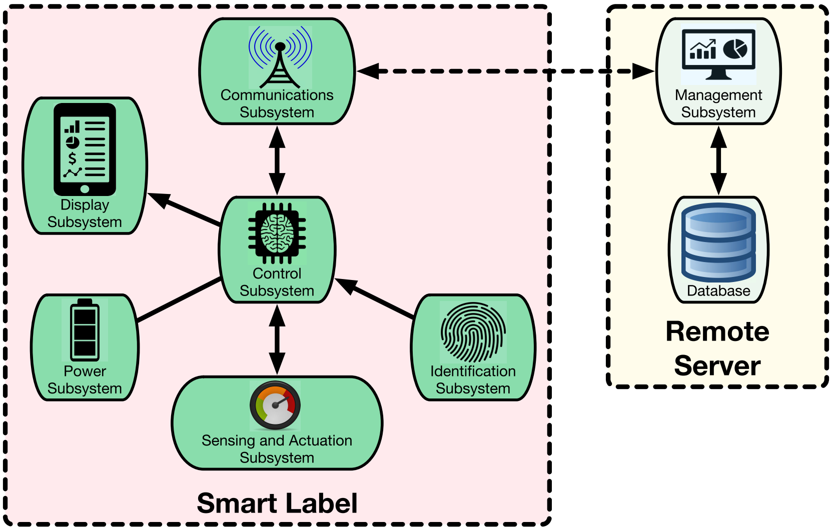

FIGURE 3. Smart label basic architecture.

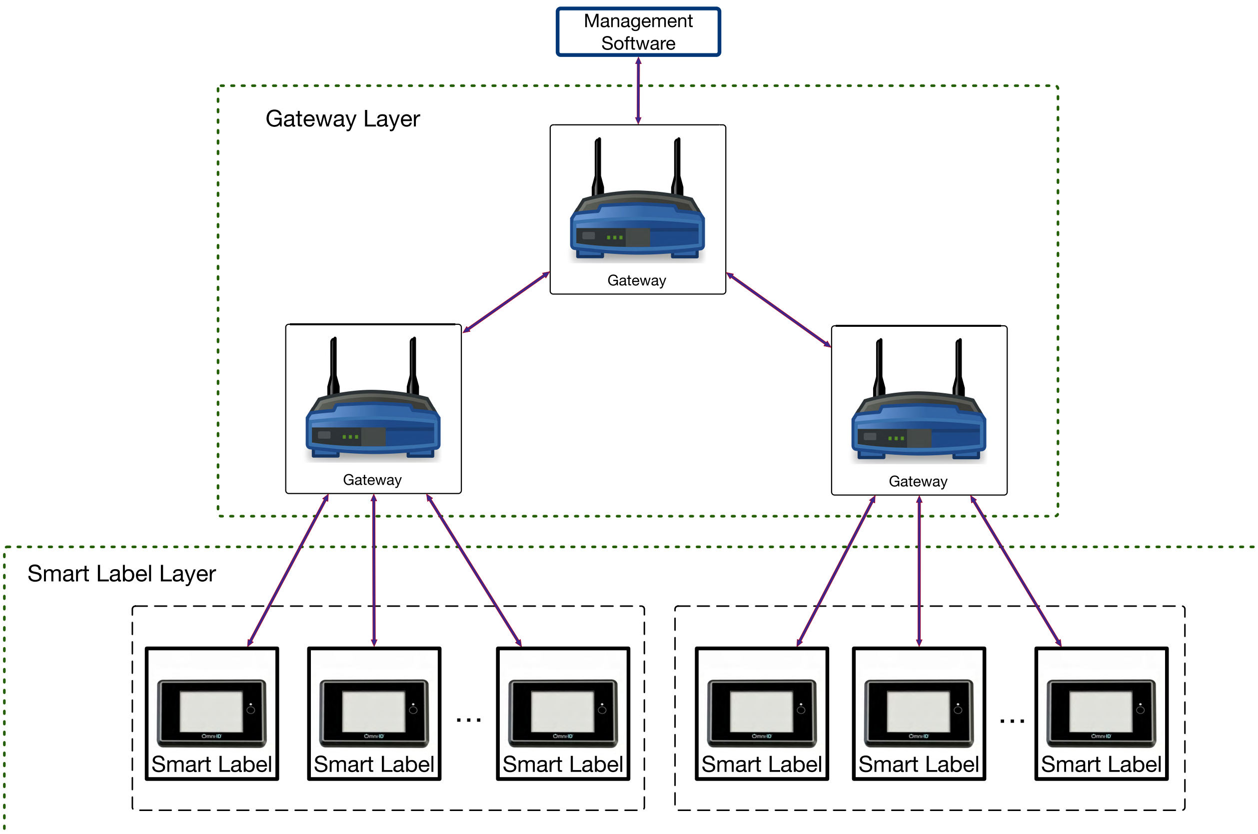

FIGURE 4. Traditional smart label communications architecture.

devices of the Gateway Layer, which route the data to/from the smart labels. When the management software has to send data to a specific smart label, it broadcasts a message to the gateways indicating that such a smart label has to update its information. When the smart label wakes up, it is checked its identifier in a pending list and the gateway sends the information to the smart label. In addition, every gateway is also responsible for managing smart label requests, whose amount has to be below a prefixed threshold [82].

This architecture is valid for most smart labeling systems, but it has a main limitation: as the number of smart labels grows, the management software (usually a single central server) becomes a bottleneck where all the requests converge. Moreover, the devices of the Gateway Layer act as mere gateways, being all the services provided by the remote management software. Thus, traditional smart labeling architectures lead to increased computational loads and network traffic on the central server (whose hardware needs to be expanded as the system grows), and increased response latencies, which impact user experience.

In contrast, Figure 5 depicts an advanced communications architecture that makes use of the edge computing paradigm to offload part of the processing from the central server. Specifically, the architecture is composed by three main layers. The layer at the bottom consists of the smart labels, which exchange data with fog computing gateways of the Fog Sublayer that provide IIoT and sensor fusion services. In addition, fog gateways can cooperate with each other in order to provide more complex services and to allow smart labels to interact among them despite the physical distance between them.

If the task to be performed is too demanding, it is delegated to the Cloudlet Sublayer, where a local cloudlet (e.g., a high-performance PC) takes over the task. If the devices of the Edge Layer are not able to fulfill the demands of a smart label, they are redirected to the cloud, where the management software and third-parties provide services.

D. SMART LABEL TECHNOLOGIES

1) IDENTIFICATION AND COMMUNICATION TECHNOLOGIES

There are different technologies that may be used by a smart label to ease product identification. The most popular modern identification technology is RFID. RFID makes uses use of radio frequency transponders that transmit unique identifiers (mainly in different Industrial-Scientific-Medical (ISM) bands) and, in some cases, certain stored data. RFID systems consist in a reader and tags that exchange information by using different wave propagation techniques [63], which require no line-of-sight to communicate and that, at short distances, usually do not need to use batteries for the tags. There exist different global standards [93] that have been used in many applications in the last years. A detailed description on the principles of RFID is out of the scope of this article, but the interesting reader has good overviews on the technology and the types of RFID systems in [63] and [93].

An evolution of RFID is Near-Field Communications (NFC) [94], which is mostly dedicated to short distance communications (usually less than 30 centimeters). What is special about NFC devices is that they can change their roles, acting in some time instants as readers and later as tags, what adds flexibility to the communications.

RFID use on industrial environments has grown remarkably in the last years [95], but there are other technologies that are competing to provide more complex interactions with the products. Such technologies are mainly communication technologies that have been re-purposed to provide, at the same time, identification and a communications channel.

An example is Bluetooth Low Energy (BLE), also known as Bluetooth Smart, which is a generic Wireless Personal Area Network (WPAN) technology for short distance communications in the 2.4 GHz ISM band. Most BLE devices have a range of up 10 meters, but industrial devices may reach 100 meters [96]. BLE makes use of different profiles depending on the type of communications, existing specific devices called ''beacons'', which are lightweight devices that emit periodically a signal that allows them to be located and identified by other BLE devices, being specially useful for indoor location [97], [98] and certain IoT applications [99]. Thus, a BLE beacon module can be used like an RFID tag for notifying the presence of a smart label.

WiFi (i.e., the IEEE 802.11 family of standards) can also be used both for identification and communications. WiFi devices work either in the 2.4 GHz or 5 GHz ISM bands that may easily provide a range of up to 100 meters in unobstructed industrial warehouses. The Medium-Access Control (MAC) address can be used to identify smart labels that carry WiFi transceivers.

Other less popular identification technologies are:

- Ultrasounds. They are usually applied in positioning systems, but they can also be used for identification. Such a kind of technologies emit sound waves at a frequency that is over the human hearing range. Identification is possible by sending unique codes.
- Infrared. They transmit pulses in a part of the light spectrum that cannot be viewed by humans. They are very popular in appliances like TVs, but they require line-of-sight between the transmitter and the receiver. Like ultrasounds, identification is performed by sending unique codes.
- ZigBee [100]. It is a set of communications protocols based on IEEE 802.15.4 PHY and MAC layers that is aimed at creating low-energy consumption Wireless Sensor Networks (WSNs). They are able to create mesh networks that extend the communication range. They operate mainly in ISM Ultra-High Frequency (UHF) bands and at 2.4 GHz. The identification can be carried out easily through the unique MAC address assigned to every node.
- LoRA (Long-Rage Wide Area Network) [101]. It is a low-energy consumption wireless technology designed for creating wide area and secure IoT networks. It operates just under 1 GHz and is ideal for WSN applications. LoRA devices can be identified by their device address.
- Dash7 [102] is a sort of active RFID technology that provides low-energy consumption long-range communications in sub-1 GHz bands. Dash7 devices may be identified at the Link Layer by the TADDR (Target Address), which can be a 2-byte Virtual ID or an 8-byte UID (Unique ID).
- Ultra-Wide Band (UWB) is a technology that performs low-energy wide-bandwidth communications. It is

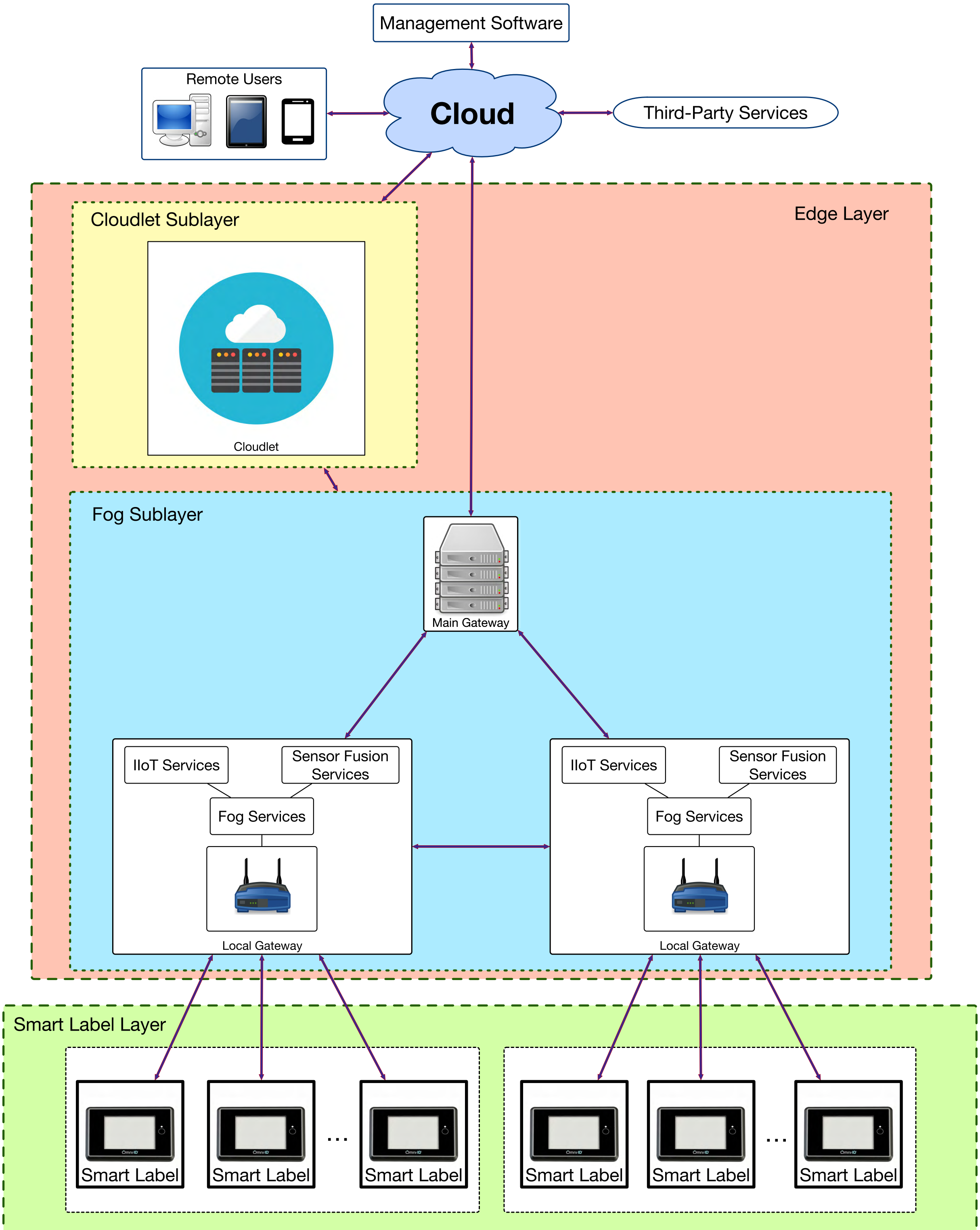

FIGURE 5. Advanced smart label communications architecture.

usually aimed at short-range indoor applications. UWB systems can use internal IDs or addresses to identify the communicating devices.

- There many other technologies that have already been used for providing both communications and identification, like WirelessHART [103], RuBee (IEEE standard

1902.1), Z-Wave [104], Insteon [105], SigFox [106], ANT+ [107], EnOcean [108], Weightless-P [109], Wi-SUN [110] or IEEE 802.11ah, among others.

Table 3 shows a comparison on the main characteristics of the latest and most popular communications and identification technologies that could be used for smart labels, indicating their frequency band, usual maximum range, data rate, power consumption, relevant features and some examples of applications that have made use of each technology.

2) POSITIONING TECHNOLOGIES

Positioning is easy in most outdoor scenarios thanks to Global Navigation Satellite System (GNSS) technologies like Global Positioning System (GPS), Galileo or Global Navigation Satellite System (GLONASS). However, indoors, positioning becomes tricky and, in general, less accurate due to the multipath effect caused by reflections [111]. Nonetheless, indoor positioning techniques have been studied thoroughly in the last years and they can be applied to most of the identification/communication technologies mentioned in the previous subsection [112], [113].

For instance, WiFi and BLE devices can be tracked by using four basic kinds of techniques:

1) **Based on Received Signal Strength Indicator (RSSI)**. This type of techniques process the RSSI received from the tracked wireless device. They can obtain good accuracy for area positioning level [18], [19] and they are usually cheap, but their stability fluctuates due to the impact of the environment and depends on the hardware used [114].
2) **Fingerprinting**. It consists in storing the RSSI or Received Signal Strength (RSS) in a database that associates the received signal strength of different access points or beacons with a specific location, assuming that, due to indoor propagation, such an association is unique (like a fingerprint) for every location [115]. However, changes in the environment influence the collected fingerprints, so in dynamic environments the database has to be updated periodically or use some kind of dynamic calibration [116].
3) **Angle of arrival (AOA)**. It is based on the capability of the system to determine the direction of arrival of the received signal [117].
4) **Time of arrival (TOA) and time difference of arrival (TDOA)**. They estimate distance by calculating the time required by the signal to arrive at certain point or the successive time differences when arriving at the receiver. These techniques depend on using accurate internal clocks, although TDOA removes the TOA requirement of having to synchronize the transmitter and receiver clocks [118].

Other technologies like ultrasounds make use of sonar/radar-like measurements by evaluating the echo produced when sound waves impact an object or the TOA between a transmitter and a receiver [119]. Infrared systems work in a similar way, but by measuring the time required by a line-of-sight non-visible light transmission [120].

3) DISPLAY TECHNOLOGIES

Traditional labeling systems do not generally use displays to show information, but rely on paper/plastic printed tags or external reading devices. This is mainly due to cost and energy consumption, but at the expense of only showing static information and having to use additional external reading devices that are usually expensive (due to the ruggedness required in industrial environments), may not be practical in some scenarios (e.g., when operators need to use both hands continuously) and sometimes they are only carried to perform a specific action (e.g., it might be fairly easier to just push a button in a smart label to indicate the event).

Therefore, the external display is essential for visualization and interaction. Display cost is still high for certain types of displays while they are not massively produced, but energy is probably the main challenge. Among the different technologies, traditional Liquid-Crystal Displays (LCDs) have become cheaper and offer different variants with diverse characteristics (e.g., Twisted Nematic (TN) and Super-Twisted Nematic (STN) types are cheap, but offer a poor viewing angle, and while Vertical Alignment (VA) and In-Plane Switching (IPS) LCDs are more expensive, they improve viewing angles). However, almost all LCD variants (except, for instance, Zenithal-Bistable Displays (ZBDs) [121]) need to be refreshed roughly 30 times per second (in spite of not showing new information), being only the backlight responsible for up to 40% of the power used in an electronic product [82]. These facts imply that, in general, LCD technology is not the best fit for smart labels whose battery life is important.

In contrast, electronic-ink (e-ink) displays only use power during the process of updating the shown information. Such a power depends on the display size. No power is consumed when the information is displayed and there is no backlight, so battery life is increased remarkably [122].

Organic Light-Emitting Display (OLED) technology is also becoming increasingly popular in electronic devices thanks to its color definition, fast response time, wide viewing angles and high brightness/contrast [123]. There are multiple OLED variants, which are classified in Active Matrix OLED (AMOLED) and Passive Matrix OLED (PMOLED). The main advantage of OLED is its low power consumption: a backlight is not required and only the pixels that are switched on are actually powered, what means that they consume 20-80% of an LCD of the same size [123]. Nonetheless, OLED displays are still expensive.

There are other potential technologies that can be used in a smart label, like Electroluminescent Displays (ELDs), but the most popular and available commercially are the three previously mentioned (LCD, e-ink, OLED). Among them, e-ink is clearly the one with less power consumption [122] and is currently the best fit for smart labels, although it must be noted that such displays are usually monochrome and they

TABLE 3. Main characteristics of the most relevant communications and identification technologies for smart labels.

Technology	Frequency Band	Maximum Range	Data rate	Power / Main Features	Popular Applications
ANT+	2.4 GHz	30 m	20 kbit/s	Ultra-low power, up to 65,533 nodes	Health, sport monitoring
Barcode/QR	–	<4 m	–	LOS, very low cost, visual decoding	Asset tracking and marketing
Bluetooth 5 LE	2.4 GHz	<400 m	1,360 kbit/s	Low power and rechargeable (days to weeks)	Beacons, wireless headsets
DASH7/ISO 18000-7	315–915 MHz	<10 km	27.8 kbit/s	Very low power, alkaline batteries last months to years	Smart industry and military
EIB/KNX RF	868 MHz	–	16.4 kbit/s	Up to 256 nodes per line	Home and building automation
EnOcean	868-915 MHz	300 m	120 kbit/s	Up to 2^{32} nodes	Energy harvesting building automation applications
HF RFID	3–30 MHz (13.56 MHz)	a few meters	<640 kbit/s	NLOS, low cost	Smart Industry, payments, asset tracking
Infrared (IrDA)	300 GHz to 430 THz	a few meters	2.4 kbit/s – 1 Gbit/s	Security, high-speed	Remote control, data transfer
IQRF	868 MHz	hundreds of meters	100 kbit/s	Low power and long range	Internet of Things and M2M applications
Insteon	902-924 MHz	45 m	13,165 kbit/s	Up to 2^{42} nodes	Home automation, access control
LF RFID	30–300 KHz (125 KHz)	<10 cm	<640 kbit/s	NLOS, durability, low cost	Smart Industry and security access
NanoNET	2.4 GHz	900 m	2 Mbit/s	Up to 2^{48} nodes	Home and building automation
NB-IoT	LTE in-band, guard-band	<35 km	<250 kbit/s	Low power and wide area	IoT applications
NFC	13.56 MHz	<20 cm	424 kbit/s	Low cost, no power	Ticketing and payments
RuBee	131 KHz	30 m	8 kbit/s	Magnetic propagation	Applications with harsh electromagnetic propagation
LoRa	2.4 GHz	kilometers	0.25–50 kbit/s	Long battery life and range	Smart cities, M2M applications
SigFox	868-902 MHz	50 km	100 kbit/s	Global cellular network	Internet of Things and M2M applications
UHF RFID	30 MHz–3 GHz	tens of meters	<640 kbit/s	NLOS, durability, low cost	Smart Industry, asset tracking and toll payment
Ultrasounds	>20 kHz (2–10 MHz)	<10 m	250 kbit/s	Based on sound wave propagation	Asset positioning and location
UPB	4–40 KHz	500 m	480 bits/s	64,000 nodes over AC power line	Home automation
UWB/IEEE 802.15.3a	3.1 to 10.6 GHz	< 10 m	>110 Mbit/s	Low power, rechargeable (hours to days)	Fine location, short-distance streaming
Weightless-P	License-exempt sub-GHz	15 Km	100 kbit/s	Low power	IoT applications
Wi-Fi (IEEE 802.11b/g/n/ac)	2.4–5 GHz	<150 m	up to 433 Mbit/s (one stream)	High power, rechargeable (hours)	High-speed, ubiquity
Wi-Fi HaLow/IEEE 802.11ah	868-915 MHz	<1 km	100 Kbit/s per channel	Low power	IoT applications
WirelessHART	2.4 GHz	<10 m	250 kbit/s	HART protocol	Wireless sensor network applications
Wi-Sun/IEEE 802.15.4g	<2.4 GHz	1000 m	50 kbit/s – 1 Mbit/s	Field area networking, Home area networking	Smart grid and metering
Z-Wave	868-915 MHz	100 m	40 kbit/s	Very low power, alkaline batteries last months to years, up to 232 nodes	Home automation
ZigBee	868-915 MHz, 2.4 GHz	<100 m	20–250 kbit/s	Very low power (batteries last months to years), up to 65,536 nodes	Smart Home and industrial applications

required ambient light, which may not be available in certain industrial scenarios.

Finally, it is worth emphasizing that an in-depth analysis of the previously mentioned technologies and its power consumption is out of the scope of this article, but the interested reader has an excellent review in [122].

4) PROCESSING UNIT TECHNOLOGIES

There are different types of electronic devices that can be integrated in a smart label to act as processing units. Some of them, like the traditional Central Processing Units (CPUs) used in PCs, are powerful but consume too much energy. Microcontrollers are usually selected because they consume less energy, they can be reprogrammed easily and they are powerful enough for carrying out the tasks performed by a smart label.

There are also other devices that could be used in a smart label like Field-Programmable Gate Arrays (FPGAs), Application-Specific Integrated Circuits (ASIC) or System-On-Chips (SOCs). FPGAs can be really powerful for performing certain deterministic demanding tasks, but development is not as easy as with microcontroller and they consume more power than other devices due to the need for powering the used logic continuously. ASICs are designed explicitly for specific applications and thus they are extremely powerful (since they have been optimized for these applications, their power consumption can be minimized). However, the cost of developing an ASIC is really high (millions of US dollars) and it only compensates when a really high amount of devices is going to be produced. Regarding SoCs, they integrate in a single integrated circuit a powerful microcontroller and several peripherals (e.g., wireless transceivers), what makes them consume more power than traditional microcontrollers.

V. FUTURE CHALLENGES

While smart tags (i.e., electronic devices that identify a product but that do not necessarily display information on them) have been used in the last years in different industrial fields, smart labels are still an emerging topic that gathers contributions from traditional labeling systems, IIoT, cloud/edge computing and sensor/actuator technologies. Although this article has described the main challenges that arise when implementing smart label systems in industrial environments, there are other issues that future developments would have to address before their massive deployment:

- Impact of environmental conditions. The conditions of the environment (e.g., relative humidity, temperature, pH, salinity...) influence smart label operation, so they have to be taken into account when designing and selecting smart label hardware. The e-ink display is probably the most critical part of hardware, since current technology has problems, for instance, with low and high temperatures.
- Ruggedness. Smart labels have to withstand the harsh conditions that are usually present in industrial scenarios. Thus, smart labels should tolerate drops, a certain amount of pressure or external impacts. It is a special concern the resistance of e-ink displays.
- Propagation of communications in the presence of metal. Many industrial scenarios are characterized by the presence of massive amounts of metal that influence traditional electromagnetic wireless communications and positioning systems [124]. Therefore, smart labels have to tolerate the presence of metal or use non-electromagnetic based communications (e.g., based on light, ultrasounds or pure magnetic communications).
- Tolerance to interferences and jamming. Smart labels are based on the premise that robust reliable wireless communications are available, so if communications are blocked or jammed (unintentionally or on purpose), the system has to be able to detect, recover and provide alternative communication mechanisms (e.g., backup communication interfaces).
- Accurate indoor positioning. Despite the effort made by the research community in designing and improving indoor positioning systems, there are still industrial scenarios where accurate positioning is still a challenge. For instance, electromagnetic-based location systems decrease remarkably its accuracy in the presence of metal. Moreover, the quest for a low-cost and generic industrial indoor positioning system is still on.
- Cost. The cost of smart labels is still high in comparison to traditional labels and RFID tags. As it could be observed in Table 1, the unitary price of the latest smart labels fluctuates between US $65 and $490, what prevents many factories from carrying out massive deployments.
- Reading distance, energy consumption optimization and battery life. Traditionally, there had to be a trade-off between reading distance and communications energy consumption: the further the communications distance, the higher the energy consumption. Nonetheless, some of the latest Low-Power Wide-Area Network (LPWAN) technologies like LoRa and SigFox have decreased remarkably the energy spent on communications, so their use should be studied further. In addition, it must be noted that some small smart labels currently can provide a battery life of several years, but when displays reach more than 5-inches, battery life decreases to months and even to weeks or days, so the overall label energy consumption should be optimized to provide the longest possible battery life.
- Scalability. Current ESL systems are already able to handle thousands of smart labels in real-time, but communications are mainly unidirectional (from the management system to the labels) and with small payloads. However, the future average Industry 4.0 smart label system would require to communicate and synchronize several thousands of labels that will receive commands, signal events and will transmit larger payloads (for instance, due to the need for showing multimedia content). Therefore, future

smart label systems, like other IIoT systems, will have to take into account scalability to fulfill the requirements of the labeling system.

- New materials. The vast majority of smart labels are based on silicon materials, but an emerging topic is the development of electronic organic labels. Such labels can be produced cheaper and with only a printer, but, as of writing, although some interesting designs have been proposed [125], they cannot be as small as traditional silicon labels and their reading ranges have to be studied and improved [126].
- Flexible electronics is also an emerging field that enables printing sensors, transistors and foldable displays on paper or plastic substrates. Fully printed systems still have certain performance limitations, but they are already allowing for developing smart labels [127].
- Zero-power identification. In order to reduce the need for batteries and to remove energy-consuming circuitry for identifying objects, new fields like smart skins, chipless RFID and zero-power identification have evolved significantly in the last years [128], [129], so they could be applied to smart labels in the near future.
- Human factors/ergonomics and usability techniques. In order to create a human-centered smart label system, the first step is to determine who are the operators, how, where, and what they are using, and what they would like to use in the future. The next step is to set relevant and realistic usability goals for their user interface. These objectives include, for example, the time to accomplish the task or the error tolerance. The final step is to perform usability testing and starting with a prototype. Through iterative design improvements and an evaluation, the final product will be difficult to use incorrectly. For instance, long-term monitoring of the use of the smart label system will be needed [1].

VI. CONCLUSIONS

This paper described how smart labels can provide identification, tracking, sensing, event detection and interaction to human-centered Industry 4.0 applications. After studying the foundations and challenges of Industry 4.0, the most relevant traditional industrial labeling systems were analyzed, determining their limitations respect to smart labels. Then, the essential subsystems that conform a smart label were detailed together with potential technologies to implement them. In addition, a traditional smart label architecture was studied together with its constraints, thus proposing a novel advanced communications architecture based on edge computing. Finally, the most relevant future challenges were briefly summarized.

After such a thorough analysis, it can be stated that smart labels can bring many benefits to diverse Industry 4.0 scenarios, but, as of writing, such scenarios present diverse challenges that should be addressed properly. Moreover, there are only just a few commercial systems and they are expensive. Therefore, although smart labels are a promising tool, more research is still required in the coming years.

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