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Self-Aware Smart Products: Systematic Literature Review, Conceptual Design and Prototype Implementation

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Abstract

The fourth industrial revolution makes more effective use of data generated during manufacturing processes and creates a more interconnected manufacturing network. The data stored inside a product can be updated, analyzed and protected throughout its life cycle. It is currently becoming a reality to speed up the modern mass-customization. The aim of this paper is firstly to explore the state of art about smart products through a systematic literature review. Second, to design a self-aware smart product in a smart factory production environment based on the review findings. Finally, to turn the conceptual design into a prototype implementation.

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Keywords: Smart Products; Intelligent Products; Smart Factory; Industrie 4.0; Systematic Literature Review; CPS; IoT; RFID

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1. Introduction

The fourth industrial revolution, namely industry 4.0, is commonly recognized as the technical integration of Cyber-Physical System (CPS) [1] into manufacturing and logistics and the use of Internet of Things (IoT) [2] in industrial processes [3]. It is the key to make an interconnected manufacturing industries scenario all around the

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world. More specifically, in which, machines can communicate not only with each other (Machine to Machine or M2M), but also with products [4]. This scenario demands smart products to know themselves [5], namely, self-awareness.

During a product's life cycle, so much data are generated, which, usually, only a small part of them are used for the manual or semi-automatic decision making [6]. However, once certain data could be stored inside the product, which carries them throughout its lifecycle, those decision making processes would be realized, with the support of those data, automatically and also in real-time [7]. With that, machines and products can then really communicate with each other. Meanwhile, customers can also participate in the design, manufacturing or maintenance of their own products by embedding their specific needs, for speeding up the mass-customization.

The main objectives of this paper are (1) to explore the state of the art about smart products and (2) to realize the discovered results as a smart factory prototype. The present paper shows on Section 2 the applied systematic literature review method and its main findings. Based on them, Section 3 firstly provides the conceptual design of a self-aware smart product together with its production environment, and then demonstrates the current results of the prototype implementation. Finally, Section 4 concludes this paper and points out future works.

2. Methods and Findings

2.1. Systematic Literature Review (SLR)

The main research question that the paper intents to address is: *What is a Smart Product?* More specifically, it is subdivided into the following three sub-research questions: (1) *Q1: What is the Evolution of Smart Product Definitions?* (2) *Q2: Which are the Enabling Features of a Smart Product?* (3) *Q3: What are the Existing Smart Product Applications?* In order to more neutrally collect and analyze data in an outcome unpredictable situation [8], this research applied the Systematic Literature Review (SLR) method [9,10] and also followed the principles that outlined in the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) Statement [11].

Firstly, to collect a comprehensive set of papers from the existing literature, the search string was constructed by combining the operator "or" between "*Smart Product*" and its synonym, "*Intelligent Product*". The reference database *Science Direct* was used during the systematic search. All collected papers should satisfy the following four conditions: (1) they were published online before the February of 2017; (2) they contain at least one of the two search terms in their titles, abstracts, or keywords; (3) they were published in journals, conference proceedings or book series; and (4) they were written in the English language.

Second, to ensure that all collected papers could be objectively assessed, Table 1 explicitly lists five main inclusion and exclusion criteria together with their subsets. Based on them, the initial review process was carried out to briefly review the paragraphs where "*Smart Product*" or "*Intelligent Product*" appeared. Besides those papers without full-text to be accessed (*WF* in Table 1), this process aims to exclude those that (1) are not academic (*NA* in Table 1) and (2) are not focusing on the smart or intelligent product research (*LR-1* and *2* in Table 1). After that, all the eligible papers were studied in detail, and organized into the corresponding inclusion categories (*PR* and *CR* in Table 1).

Table 1. Inclusion and exclusion criteria.

I/E	Criteria	Criteria Explanation
Inclusion	Closely Related (**CR**)	It is focusing explicitly and specifically on the research of smart or intelligent products.
	Partially Related (**PR**)	Its focus is not about smart or intelligent products, only part of its contents is related.
Exclusion	Without Full-text (**WF**)	We do not have access to its full text.
	Non-Academic (**NA**)	It is not an academic paper, such as, editorial materials or company profile.
	Loosely Related (**LR**)	It is not focusing on the research of smart or intelligent products and also without definitions. LR-1: Smart or intelligent product are only appeared once, twice or thrice as a cited expression; LR-2: Smart or intelligent product are only used as a part of another noun phase;

Based on this searching method, in total 105 papers were collected during the initial review process. Fig. 1 shows the number of papers that were included or excluded according to the criteria listed in Table 1. Finally, 53 papers were included and entered the final review process. Each included paper was closely exanimated and the corresponding data of interests were collected: (1) The *publication year* and the *definition* of a smart product for *Q1*; (2) The *sentences* that contained *Smart Product* or *Intelligent Product* for *Q2*; (3) The *application examples* of a smart product for *Q3*.

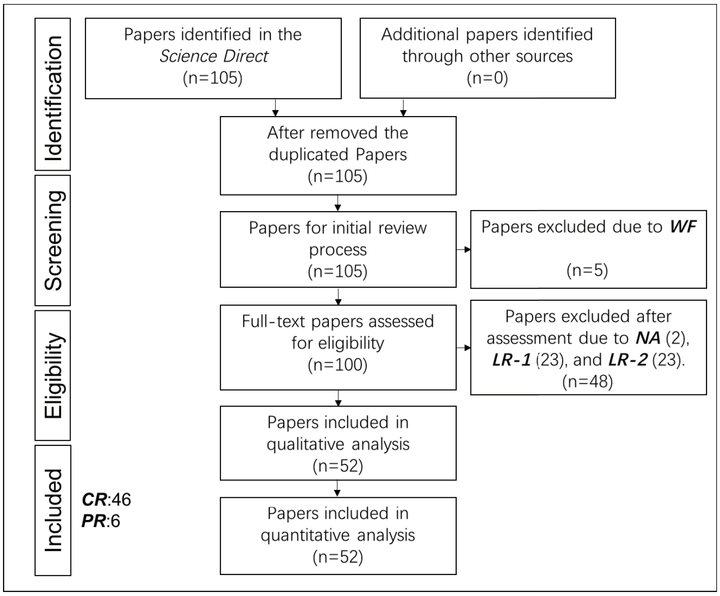


Fig. 1. The Systematic Literature Review Phases based on the PRISMA Flowchart.

2.2. SLR Findings

2.2.1. Q1: What is the Evolution of Smart Product Definitions?

Even though the notion a smart product was proposed, at least, more than twenty five years ago [12], which is still rather undecided [13]. Various kinds of definition, which focus on certain perspectives, have been suggested, discussed, and changed along the development of production research [14]. In order to provide a more comprehensive and neutral view, the collected definitions from the SLR were, first, qualitatively analyzed (the extraction and classification of points), and then, quantitatively summarized (the calculation of citations).

As the first SLR finding, Fig. 2 illustrates the evolution of definitions. In 1990s, a smart product was generally defined as a *physical product* with embedded *information technologies*, namely *IT* (such as, software program and sensors) [12,15,16]. In 2002, one of the most cited smart product definition was presented. Based on this SLR, 25.0% of the total included papers (13 papers) have referenced to this definition [17]. In which, the *information based representation* of a product should enable its *physical representation* to:

i. possess a unique identification;
ii. effectively communicate with its environment;
iii. retain or store data about itself;
iv. deploy a language to display its features, production requirements etc.;
v. participate in or making decisions relevant to its own destiny.

After that, the investigation of smart product was continued, each above-mentioned feature was further specified (Section 2.2.2). In 2008 and 2009, the concept of *information based representation* was further subdivided as *intelligent being* (as a mirror of the product's existence) and *Intelligent agent* (responses for decision making activities) by [18–20]. Additionally, in 2010, [21] renamed it as a *computing entity* attached to *a product or single* *part* during the whole product life cycle in their research. Recently, in 2016, from the overall functionality perspective, it was also defined as the combination of hardware functions (e.g. mechanical, electrical/electronic functions) and software functions [22]. Finally, in the context of Industry 4.0, as it was pointed out by [23], a smart product can be considered as a cyber physical system, which "additionally use and intergrade Internet-based service in order to perform a required functionality".

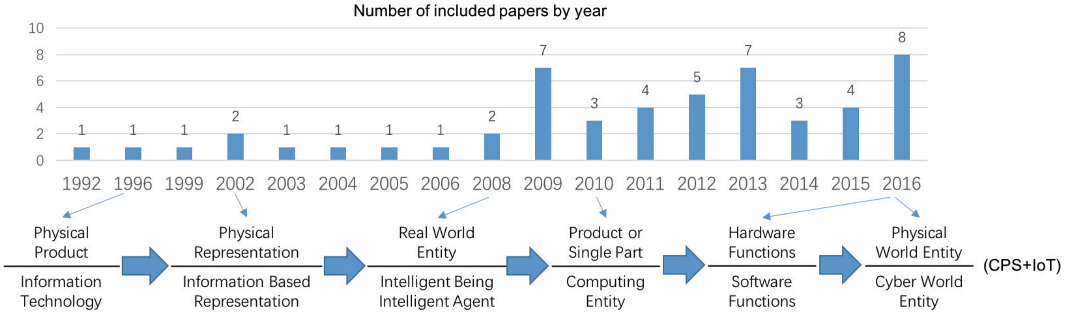


Fig. 2. The Quantitative Summary of Smart Product Definitions

2.2.2. Q2: Which are the Enabling Features of a Smart Product?

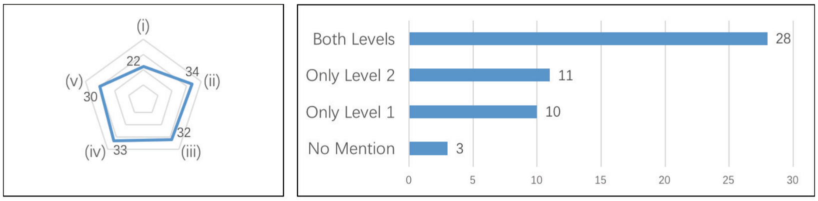
According to [24], the five main features of a smart product defined in [17] (Section 2.2.1) was progressively divided into two levels of Product Intelligent (PI):

- PI level 1 allows a product to communicate its status, for example, form, composition, and location. It essentially covers the feature (i), (ii) and (iii).
- PI level 2 allows a product to assess and influence its function in addition to communicating its status. It therefore covers from the feature (i) through to the feature (v).

The qualitative analysis of the collected 937 *sentences* that contained *Smart Product* or *Intelligent Product* was performed. The papers which those sentences belong to were quantitatively summarized (calculation of frequency) into corresponding features and PI levels (see Fig.3). Note that, this qualitative analysis only took into account the explicit feature descriptions. For example, "smart products like to talk to each other, and the conversation is in a whole new language" [15] was classified as an explicit expression of feature (iv). Meanwhile, this analysis disregards the mentions to features in a general sense, such as, "Mechatronics, which focuses on the synthesis of mechanics and electronics, has gained much ground in recent years and is vital for the building of smart products." [25].

Fig. 3 (a) illustrates the number of included papers from the five main features perspective. It can be found that, the feature (ii), (iii), (iv), and (v) received more balanced distribution of research efforts with one another, which ranging from 57.7% (30 papers) to 65.4% (34 papers). In comparison, the feature (i) ends up to be the most neglected one. In this SLR, only 22 included papers have covered this feature in their smart product descriptions.

Fig. 3 (b) shows the quantity of included papers from the product intelligent level perspective. On one hand, except the three papers that do not explicitly provide feature-related descriptions, more than half (53.8%) of them cover both PI level 1 and 2. They contain *sentences* that related to one or more features in corresponding levels. On the other hand, it can also be found that, there still exists around 21.2% of them (11 papers) presents their contribution directly in PI level 2, but without mentioning PI level 1 as its foundation.



(a) Number of Papers by Feature (b) Number of Papers by Product Intelligent Level

Fig. 3. The Quantitative Summary of the Enabling Features of a Smart Product

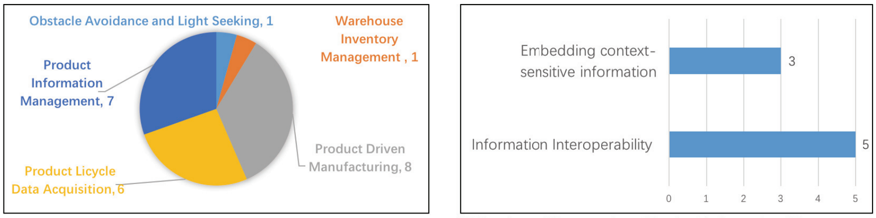
Additionally, a further investigation was carried to discover other possible enabling features. It turns out that, even though they are less common, several interesting ones emerged, for example, a smart product should also be able (1) to reduce CO_2 emission, energy usage and environment damage [4,26,27]; (2) to be personalized by customer from the design to manufacturing [28–30]; (3) to learn and improve based on user experiences [31].

2.2.3. Q3: What are the Existing Smart Product Applications?

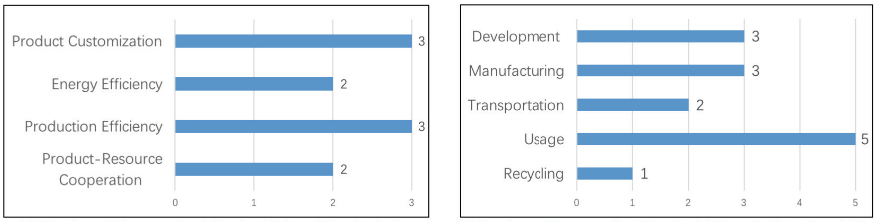
The qualitative analysis of collected *application examples* is based on the 46 papers that were classified as Closely Related (CR in Table 1). Then, the SRL finding was quantitatively summarized as Fig. 4 (a). In total, 50.0% of them (23 papers) that contain case studies related to smart or intelligent products. However, among them, laboratory experiments account for 82.6% (19 papers) [7,13,23,28,29,32–45]. For the rest 17.4% (4 papers), they are presented as industrial applications [46–49].

More specifically, from the application filed perspective, the following three research directions were discussed:

- *Product Information Management* (see. Fig. 4 (b)). In which, 5 of them specifically focused on enhancing information interoperability [13,23,38,42,46] through models or standards. And the other 3 committed themselves to the research about embedding context-sensitive information on products [39,41,43].
- *Product Driven Manufacturing* (see Fig. 4 (c)). In which, [28,29,49] contributed in smart personalized product, [37,49] highlighted the increase of energy efficiency, [34,48,49] stressed the enrichment of production efficiency (e.g. optimization of planning and scheduling), and [29,35] devoted to enhance product-resource cooperation.
- *Product Lifecycle Data Acquisition* (see Fig. 4 (d)). On one hand, certain research efforts can be found about the data from development phase [40,44,45], manufacturing phase [40,44,45], and transportation phase [36,47]. On the other hand, the data from the usage phase received the most attention in this SLR (by [7,40,44,45,47]). Meanwhile, it can also be found that, only one of them [7] is related to the data from recycling phase.



(a) Number of Papers by Application Field (b) Number of Papers about Product Information Management



(c) Number of Papers about Product Driven Manufacturing (d) Number of Papers about Product Lifecycle Data Acquisition

Fig. 4. The Quantitative Summary of Existing Smart Product Applications

3. Design and Implementation

Based on the SLR findings about the definitions and enabling features, presented in Section 2.2.1 and Section 2.2.2, a conclusion can be drawn. A smart product should be able to carry data about itself. Those data are collected along its product life cycle, which then can be stored, updated, and used in real time due to the Internet connectivity. Especially along the production line, this self-contained data can be used to improve the decision-making process, for example, by automatizing it. In terms of automation and industrial revolution, such ability of a smart product is called self-awareness.

The SLR finding about the application examples, presented in Section 2.2.3, indicates a list of existing research directions. However, the research efforts of these three main ones are isolated from each other. There is still a lack of a general framework that can capture the overall picture. Furthermore, as one of the key participants within the fourth industrial revolution [3], the research about smart products has not yet received sufficient attention [50]. Among the included papers, only 7.7% of them ([28,44,45,49]) have explicitly mentioned "industry 4.0", and only 3.8% of them ([23,49]) have explicitly highlighted the importance of CPS.

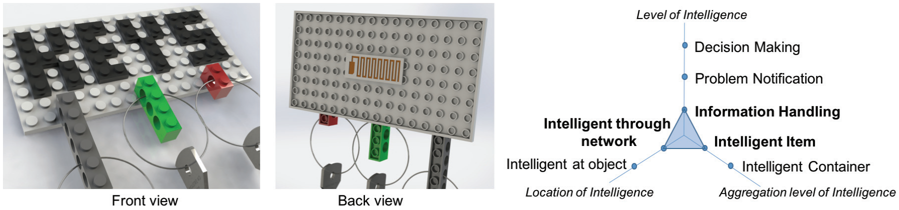
To follow the conclusion of a smart product, and also to address those discovered drawbacks, the design (Section 3.1) and implementation (Section 3.2) of a self-aware smart product together with its production environment (smart factory) are presented in this section.

3.1. Conceptual Design of the Smart Product

This experiment was carried out in the automation control department of Pontifical University Catholic of Paraná (PUCPR). As the initiation of a smart factory laboratory, the first smart product is a Lego Key Holder (see Fig.5 (a)).

From the definition and feature perspective, the smart product is designed to achieve all the preliminary degree of the three orthogonal dimensions (see Fig. 5(b)) inside the smart product classification model [14]:

- *Information handing*. The smart product should be able to mange its own data, given by sensors. At this degree, the full control of this product exists externally.
- *Intelligence through network*. The intelligence of the smart product is outside of its physical world entity, at a different location. At this degree, the embedded device acts as an interface to the intelligence.
- *Intelligent Item*. The smart product only manages data, notification and/or decision about itself. At this degree, all its components cannot be distinguished as individual objects.



Front view Back view

(a) Lego Key Holder

(b) Classification of the Smart Product

Fig. 5. The Conceptual Design of the Lego Key Holder

From the application perspective, the production environment of this smart product, namely smart factory, was designed to achieve the following three requirements though combining existing technologies, such as: sensor and IoT technologies:

- *Product Lifecycle Data Acquisition.* To collect data related to the smart product from the initial development phase to the final recycling phase.
- *Product Information Management*. To store and update data related to the smart product without interoperability issues, and to use and protect those data in real-time.

- *Product Driven Manufacturing*. To cooperate the smart product and equipment for enabling many varieties on one single production line, and to process specific customer needs for enabling the mass customization.

3.2. Prototype Implementation of the Smart Factory

3.2.1. Application Scenario

As can be seen from Fig.6, this scenario starts by the costumers, who will either design their own Lego Key Holders or chose some existing ones through a mobile (web) application connected to the cloud service (IBM Bluemix). Such personalized design will be stored or updated into both (1) the cloud database (IBM Cloudant), and also (2) the RFID tag attached to the smart product via the Data Access Station one (DAS-1). In which, a Raspberry Pi provides the Internet connectivity to the cloud service and a MFRC522 provides the RFID reading and writing ability. Later, the data carried by the smart product are used to support the automatic decision making processes of corresponding equipment along the production line.

At the DAS-2, the smart product firstly communicates with the component dispenser to drop the right type and right quantity of Lego bricks into its Work Piece Carrier (WPC). Then it advertises the gate on the conveyer to decide whether it should go to the Assembling Workshop (AW) or directly to the warehouse (in case that some customers want to assemble the product by themselves). At the DAS-3, inside the AW, the smart product communicates with the Tablet to demonstrate the graphical design of the personalized Lego Key Holder, which allows, for now, a human worker to assemble its parts. At the DAS-4, the smart product starts the communication with the Automated Guided Vehicle (AGV), created by Lego^{TM} Mindstorm, for transporting it to the right position inside the warehouse, and then informs the blocker on the conveyer to release the empty WPC for a new production cycle.

Finally, the finished products are picked up from the warehouse, packed into corresponding postal boxes by a robotic arm (Universal Robots UR5, controlled by cloud-connected Raspberry Pi), and ready to be sent to their customers. Moreover, during the production, customers can also access to the status of their own smart products in real-time through email, twitter or SMS message.

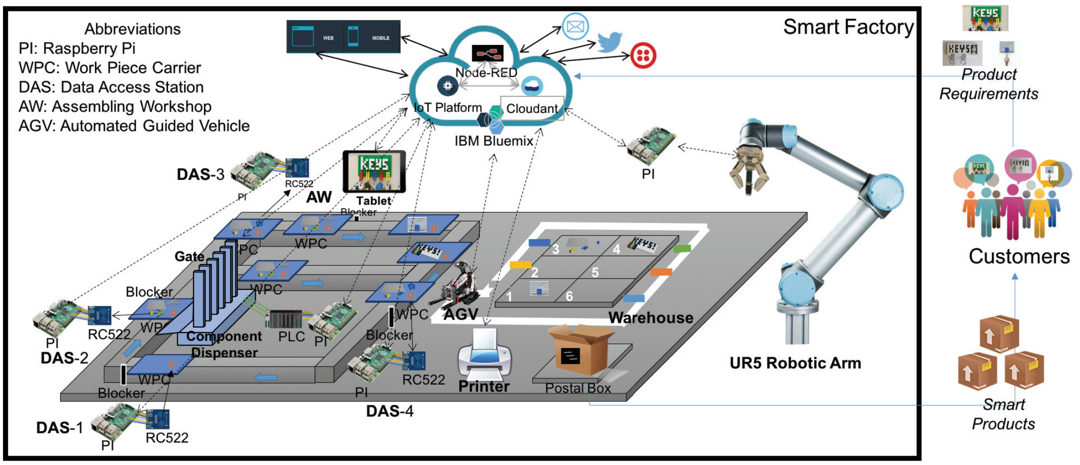


Fig. 6. The small-scale Industry 4.0 scenario for the production of self-aware smart products

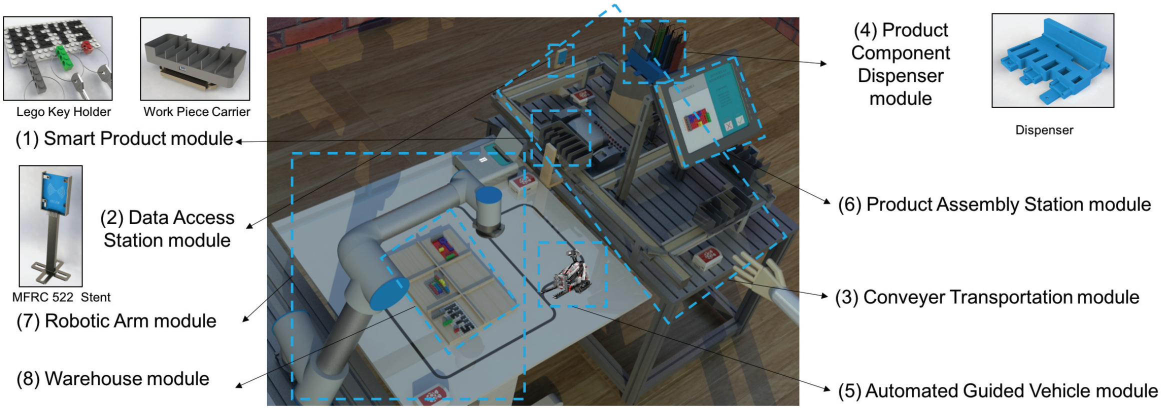


Fig. 7. Smart Factory Prototype Implementation: 3D Representation

3.2.2. Prototype Implementation

According to the definition of the CPS, the implementation of the smart factory laboratory is divide into two parts:

- *Physical World Entities:* There are eight main physical modules: (1) Smart Product module, (2) Data Access Station module, (3) Conveyor Transportation module, (4) Product Component Dispenser module, (5) AGV module, (6) Product Assembly Station module, (7) Robotic Arm module, and (8) Warehouse module.
- *Cyber World Entities*: There are also eight informational modules: (1) Product Data module, (2) RFID Data Processing module, (3) Conveyor Control module, (4) Dispenser Control module, (5) AGV Control module, (6) Product Design Display module, (7) Robotic Arm Control module, and (8) Inventory Management module.

Moreover, Industrial Internet of Things (IIoT) requites the Internet accessibility, but what's more is the interoperability of equipment along the product life cycle. Because of this fact, an additional cyber world entity, namely (9) IoT Cloud Management module, is also considered as one fundamental function of the smart factory laboratory. As can be seen from Fig. 7, the 3D representation of the smart factory laboratory is shown. In which, some parts of the above-mentioned modules have already been implemented in the automation control department of PUCPR.

4. Conclusion

According to the reference database *Science Direct*, among the 142 papers that contain the "Industry 4.0" or "Industrie 4.0" in their titles, abstracts, or keywords, there are only 16.9% of them (24 papers) have mentioned the "Smart Product" or "Intelligent Product" in their full-text, moreover, only 2.1% of them (3 papers) in their abstracts. It emphasizes the greater importance should be attached to smart products in the context of the fourth industrial revolution. Therefore, to initiate a smart factory laboratory, the SLR was carried out in the first place. It not only provides an evidence-based overview of smart product definitions and enabling features, but also indicates the existing shortcomings among different application examples. With the guidance of this review, a self-aware smart product together with its smart factory production environment were conceptually designed and currently under development. This smart factory prototype will act as an experimental environment for further "factory of the future" researches.

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