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Description Model of Smart Connected Devices in Smart Manufacturing Systems

Juergen Lenz[a]*, Dominik Lucke[b], Thorsten Wuest[c]

[a]*University of Applied Sciences Würzburg-Schweinfurt, 97070 Würzburg, Germany*
[b]*Reutlingen University, ESB Business School, 72762 Reutlingen, Germany*
[c]*Benjamin M. Statler College of Engineering and Mineral Resource, West Virginia University, Morgantown, WV 26506, USA*

Abstract

This paper presents a description model for smart, connected devices used in a manufacturing context. Similar to the wide spread adoption of smart products for personal and private usage, recent developments lead to a plethora of devices offering a variety of features and capabilities. Manufacturing companies undergoing digital transformation demand guidance with respect to the systematic introduction of smart, connected devices. The introduction of smart connected devices constitutes a strategic decision cost due to the high future committed cost after introduction and maintaining a smart device fleet by a vendor. This paper aims to support the introduction efforts by classifying the devices and thus helping companies identify their specific requirements for smart, connected devices before initiating widespread procurement. By mapping the features of these devices based on various attributes, allows the clustering of smart, connected devices including a requirement list for their implementation on the shopfloor. Four individual commercially available smart connected devices were analyzed using the description model.

Keywords: Smart Devices; Smart Products; IoT; Smart Manufacturing

1. Introduction and Motivation

A rapid adaption to the current situation is for factories more and more essential to stay competitive. Digital software tools as well as digital enabled hardware can play an important role to reach this objective. Similar to the wide spread adoption of smart products for personal private usage, recent developments lead to a plethora of devices

* Corresponding author. Tel.: +49 9721 940-8468;
E-mail address: Juergen.Lenz@fhws.de

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offered with various features and a wide range of capacities and enable a wider range of economic industrial applications. Smart devices are closely linked to the vision of ubiquitous computing [1] and smart environments with smart objects fulfilling a function autonomously. Based on this concept the current concepts of the industrial-internet-of-things (IIoT), context-aware applications and cyber-physical systems (CPS) have evolved. The worldwide market for IIoT, was rated at about 263 billion US dollars in 2021 [2]. Also, today several definitions exist for smart devices. The work of Silverio-Fernández et al. [3] integrated aspects of several definitions for smart devices before. Therefore, in this paper we use the definition by Silverio-Fernández et al. that "a smart device is a context-aware electronic device capable of performing autonomous computing and connecting to other devices wire or wirelessly for data exchange." [3]. However, the introduction of smart device enabled applications in industry is still a big and multidisciplinary challenge. Especially small and medium sized enterprises (SME) often have problems due to missing capacity and experience. A crucial step in such projects is the selection and introduction of the smart devices suitable for the envisioned use case. Here, a systematic description of smart connected devices supports the selection process the introduction by classifying the devices and helping companies identifying the specific requirements of smart devices before widespread procurement takes place. By mapping the features of these devices with various possible attributes groups of devices can be identified and a requirement list can be derived.

This paper is organized as follows: Section 2 describes the State of the Art in smart manufacturing and past research on smart devices for manufacturing. Section 3 outlines a new description model of these smart connected devices for manufacturing. In Section 4 two groups of smart devices, smart sensors and smart actors, are analyzed with the novel description model. The findings are discussed and summarized in Section 5.

2. Related Work

In the following, we briefly describe the core terminology and provide the context for the analysis and derived smart, connected devices for Smart Manufacturing (SM).

2.1. Smart Manufacturing

Smart Manufacturing (SM) describes "a data intensive application of information technology at the shop floor level and above to enable intelligent, efficient and responsive operations" [4] with a data and technology focus. The three core principles of smart manufacturing are connectivity, virtualization, and data utilization [5]. In essence, SM combines operations technology (OT) with information technology (IT) [6] and has data acquisition through sensor systems and advanced data analytics at its core, to improve manufacturing operations at the shop floor [7], factory [8] or supply chain [9] level. Overall, product and process information and data, enabling technology, and manufacturing knowledge are key elements of Smart Manufacturing Systems (SMS). SMS resemble cyber-physical systems, which provide access to large amounts of product and manufacturing process data [10]. When we look at the key technologies associated with SM, [11] identified the following ten clusters via a recent meta-analysis: (i) artificial intelligence, machine learning, and advanced simulation; (ii) cloud, fog, and edge computing; (iii) additive manufacturing, (iv) industrial internet-of-things and cyber-physical systems; (v) augmented reality, virtual reality, and digital twins; (vi) automation and robotics; (vii) cybersecurity; (viii) blockchain; (ix) smart sensor systems; and (x) 5G-networks. The new capabilities offered by 5G open up new opportunities for smart products in a manufacturing environment [12][13].

It is apparent that smart, connected devices are reflected heavily in the key enabling technologies of SMS.

2.2. Smart Devices for Manufacturing

Smart, connected devices play a role in our personal life, such as smart watches, to smart speakers, and smart fridges [14]. Recently, they also play an ever more important role in manufacturing with a more specific purpose tailored to the application domain, providing new devices, services, and apps in rapid succession [15]. Intelligent products are essential components of cyber-physical systems and big data analytics [16]. These smart, connected devices in a manufacturing context are also known as Smart Products [17] or Intelligent Products [18]. They represent physical assets that can be interacted with in variating levels of intelligence. McFarlane er al. [18] were one of the first, defining intelligent products as "*physical and information based representation of an item [...] which possesses a unique identification, is capable of communicating effectively with its environment, can retain or store data about itself, deploys a language to display its features, production requirements, etc., and is capable of participating in or making decisions relevant to its own destiny*". It has to be noted, that the degree of intelligence possessed may vary significantly [19]. In a manufacturing environment, widely used smart, connected devices include smart sensor systems that are added to machine tools to collect process data, camera systems providing data to co-bots control systems, and smart watches that monitor operators' safety and health just to name a few.

The increasing implementation raises the question how these devices distinguish themselves from a functional, feature based, and interaction perspective. The novel description model of smart connected devices for manufacturing aims to help to answer this question.

3. Description Model of Smart Connected Devices for Manufacturing

The description model of smart connected devices decomposes the devices logically. Smart connected devices have distinct functions and features. A function of a device a generic category of an operation performed by the device. Devices fulfill a specific purpose in the context of their deployment. There are many possibilities and alternative selection how the requirement addressing one of the attributes of a function. Section 3.1 gives an overview of functions of smart connected devices.

Design choices by vendors lead to features of smart connected devices. These features enable a device to address a requirement derived by the intended function of a device. Smart connected devices are a part of a CPS. Section 3.2 explains these features and possible implementations.

3.1. Functions of Smart Connected Devices

The specific intended purpose can be device can be broken down into functions, which the device has to fulfil. A choice for each of these functions is necessary in order to narrow and streamline the selection process during procurement. Table 1 shows an overview of all the described functions and possible choices (attributes), which are derived from functions of CPS [20],[21]. For each of these functions, except information processing, only attribute choice is one possible.

Table 1. General Functions of Smart Connected Device

Function	Attributes			
Application Domain	Manufacturing and Assembly	Logistic	Quality Control	Maintenance
Data Acquisition	None	Manual Input	Physical Measurement	Digital Data
Data Storage	No	Long Term	Short Term	Buffer (volatile)
Location Awareness	Not Required	Indoor-Tracking	Outdoor / Global	
Actuator	None	Hardware	Software	
Information Processing	(Raw) Value Pass-through	Locally on Device	Locally on Edge	Cloud

Application Domain: In which department is the smart device deployed? Is it manufacturing and assembly, logistic, quality control, or maintenance? Each department may have different requirements. Dust, dripping or spraying water may lead to different *Ingress Protection Code*. In addition, deployment for quality assurance may lead to higher intervals or calibration checks.

Data Acquisition: Does the smart device need to collect or generate data? For instance, the transmission of manual input. The operator is called upon to enter specific information on the spot. Another source of data is digital data such as NFC, Bar Code or QR Code. Here IDs are exchanged in order to generate context with specific process station, a unique part number or the ID of an operator. A third way of data acquisition is physical measurement. Sensors inputs are utilized to calculate physical dimension such SI-units or metrology data. In the case of “None”, a display or any kind of printer will not require data acquisition in the shop floor.

Data Storage: Does the smart device need to store data long-term, short-term or just act as a buffer? Long-term storage is required to perform analytics on the device. Short-term storage is usually the option to send chunks of payload data to the platform instead of a single transmission per newly acquired data point. Buffers function is to forward the data point in a single transmission each, with additional check functions to confirm the receipt of a transmission in order not to drop packages. This buffer usually is volatile, and data is only stored for the purpose of data transmission. No data storage is common for smart devices, which take measurements and transmit the measurement without acknowledge. In case of a transmission error data loss occurs.

Location Awareness: Is location awareness required for the device? Options here are *no location awareness*, *indoor tracking* or *outdoor tracking* on a global scale required. No location awareness is common in applications with fixed assignments of smart devices to process stations. Indoor tracking adds value for small mobile equipment, which is not permanently assignment to any station. Outdoor tracking is out of the scope for shopfloor smart devices and usually used for tracking of equipment while deployed at customer sites. This requirement is independent form the technical localization method used. Methods used such as Received Signal Strength Indicator (RSSI) or Time Difference of Arrival (TDoA) [21].

Actuators: Should the smart device be able to move or control anything on the shopfloor? Hardware actuators may be electric, hydraulic, or pneumatic. Software actuators are for instance printer driver or a robot control system. No actuators can also be a valid option, if the smart device only acquires or conveys data.

Information Processing: Is information processing necessary? If yes, the raw data acquired by the smart device requires processing. In this case, the next question is where does the information processing take place? The options are (raw) value pass-through, locally on device, locally on edge, or in the cloud. According to the knowledge ladder [22], raw data turns into information by combining the data with its meaning. The meaning of the data is already present on the device, but not all smart devices aware of its usage context, for examples see Section 4. Information processing can also be implemented as combination of pre-processing on the device or edge and computation heavy analytics in the cloud. In case the data is processed on the device, the device itself has to have adequate computing power. If all features are “None” or “Not Required”, there is no need for a smart connected device. If at least one feature has a different attribute, the smart device has a specific purpose to fulfill.

3.2. Features of Smart Connected Devices

Features of smart connected devices are decomposed into software features, hardware features and user interaction. For each of these features different implementations are possible. Different implementation may be incompatible with existing infrastructure and conflict with constraints set by the use case.

3.2.1. Software Features

Every smart connected device requires initial effort to integrate into its architectural ICT-context. For instance, configuring the connection parameters to an IIoT-platform. There are many ways to establish this connection. The features in this context are distinct aspects of this integration. For each of these features different implementations are possible. Table 2 shows an overview of the main described integration characteristics and various implementations.

Table 2. Integration Characteristics - Software of Smart Connected Device

Feature	Attributes		
Connection Type	Fieldbus-System	Ethernet/Internet Protocol	Wireless
Interface & Protocol	Open Standard	Proprietary Protocol	
Data Model Provision	No Information about Data Model available	No, Data Model implemented manually	Yes, Data Model available on the Device
Data Transmission	No Information available	Pull Request	Push, Publish–Subscribe
Security	No Information available	None	Encryption

Connection Type: By which type is the device connected to the IIoT-platform? There are three possible connection types. Either the smart device communicates over a Fieldbus-system [23], such as *Modbus, Profibus, Sercos,* or the smart device is capable of a higher IP-based protocol, or it has a wireless connection from the IEEE 802.11 oder IEEE 802.15 standards family, such as WLAN [24], *ZigBee, Bluetooth or Wize* [25]. In the case of a bus system, an edge device is required to connect the device to an IIoT-platform. In the case of an IP-based protocol, a direct connection to IIoT-platform can be established via IoT-gateways. The protocol of theses gateways is generally based on platform specific *REST APIs* or *Open Data Protocol (OData).* In case of a wireless connection, companies tend to offer closed system with a proprietary receiver station.

Interface & Protocol: Which protocol is used by the device? Regardless of the connection type, the bus-system or the IP-based protocol can be an open standard or a proprietary protocol. Examples for open standards are *Modbus* [23]*, MTConnect* [26]*,* and *OPC-UA* [27] based standards such as *Umati* [28]*,* or *EUROMAP 63* [29]. Examples for proprietary protocol are *Allen-Bradley Micro800, Beckhoff TwinCAT,* and *Siemens TCP/IP Ethernet*. In both cases, drivers are required for the integration of the smart device.

Data Model Provision: Does the device provide a data model? For each tag in the data model, additional meta information is required. Typical data information for each tag consists of variable name, variable type (string, integer, double…), and read/write permissions. This data model either is provided by the smart device itself or is implemented manually in the platform. In case of a closed proprietary system, no information about data model is available.

Data Transmission: Which transmission pattern is implemented? Once the connection is established, there are two possible data transmission patterns. Data transmission by pull request or with publish–subscribe pattern. In a pull request, the current value of a tag is requested by platform. Within a publish–subscribe pattern, tags are subscribed and, in an event, for instance a data change event, the new value is published, and all subscribers receive the data transmission message. Here the transmission can be over multiple nodes. The publisher my not be aware of the subscribers' identity. In case of a closed proprietary system, no information about the data transmission is available.

Security: What security measures are implemented? Data transmission can be secure or unsecure. Secure communication has multiple levels. Simple authorization by user/password or token is the first level. High level of securities involves encryption communication for instance via SSL certificates. In case of a closed proprietary system, no information about the communication security is available.

3.2.2. Hardware Features

The features of the hardware of the smart connected device sets constraints on the operator activity. The hardware design choices restrict the operator in performing the task on hand. Table 3 shows the overview of these hardware characteristics features and its attributes.

Table 3. Hardware characteristics - Hardware of Smart Connected Device

Feature	Attributes	
IT-Architecture	Standalone (Local Intelligence)	Depending on Private Cloud (Edge)
Power & Data Transmission	Cable Based	Battery & Wireless
Power Cycle	< 8h	> 8h

IT-Architecture: What IT-Architecture is used for the device? Either it is a standalone system or it is private cloud depended. A standalone device can be any device (Microcontroller, Embedded System, Self-Contained System) ranging from a system-on-a-chip to an industrial PC having all the necessary intelligence for the operation locally. A cloud depended device does not have the necessary intelligent to perform the operation capabilities and required computation on an edge device or on the cloud.

Power & Data Transmission: Is the device mobile or tethered? A mobile device offers more flexibility and requires less operation time. A tethered device requires less overall infrastructure such as charging station and wireless access point.

Power Cycle: Can the device be used for a longer or shorter duration compared to a standard operator shift? The threshold of a wireless device is one shift. If the device requires additional setup or change over time, the operator is subject to unproductive downtime.

3.2.3. Human-Machine-Interaction (HMI)

The user interaction with the smart device is essential for the ease-of-use and the user acceptance. In this chapter, feedback of the device to the operator is described. Table 4 shows the possible dimensions of feedback to the operator.

Table 4. Human-Machine-Interaction (HMI) with Smart Device

Feature	Attributes			
Visual	None	Signal Light	Display	AR/VR
Haptic	None	Mechanical Switches, Keys, Forces	Touch, Motions, Gestures	Vibration
Audio	None	Signal, Beep	Voice, Sound, Music	

Visual: Does the device have a visual feedback? Possible visual feedbacks are signal light, display, and AR/VR. Signal lights are for instance indicators, status or response lights. Andon lights indicated the operation status, pointing signal lights are used for pick-by-light systems. A display can be any LCD, LED, or a segment display. With augmented reality (AR) real world objects are enhanced by computer-generated information.

Haptic: Does the device have a haptic feedback? Haptic technology can create an experience of touch by applying mechanical switches, keys, or forces. Another category of haptic interaction is the group of input methods such as touch, motions, gestures. A third way of haptic interaction are vibrations in the device.

Audio: Does the device have an audio feedback? Here two attributes can be distinguished. Simple signal or beep audio can be compared to the signal light. They just convey short indication or status information. In the second category higher level of information is conveyed, such as voice feedback of as well as voice commands to the operator, or sound, music such as jingles for confirmation, orientation, or awareness raising. This higher level of information may result in higher on-board computing power.

A smart connected device may also have none of the HMI features, just for data acquisition or actuator purposes.

4. Exemplary Smart Devices

Utilizing the description model of smart connected devices outlined in section 3, four typical and commercial available smart connected devices are broken down into its functions and features. Figure 1 illustrates the identified attributes of these specific four smart connected devices. Their exemplary breakdown helps to understand the requirements and capabilities of smart connected devices in general and ultimately helps the introduction of such devices.

4.1. Smart Sensors

The first example of a smart sensor is a smart clamp meter, the *Testo 770-3 with BT connectivity and App* [30]. Its attributes are depicted in blue in Figure 1. It relies on one-way communication from the device to the platform, or to the edge and the typical use case of is physical measurement of all sorts. It is an inexpensive, lightweight device and after initial configuration for platform integration, they required no parameters during operation.

As a second example of a smart sensor, a wearable barcode reader was chosen. The specific device was a *ProGlove MARK Display* with connectivity and corresponding app [31]. The attributes of the wearable barcode reader are depicted in purple in Figure 1. It requires bidirectional communication to convey information back to the device and display it.

These two smart sensor systems have in common. They have no, or minimal data storage capabilities, the intent is to forward the data as fast as possible and disregard the current data point in order to be ready to acquire a new data point. No location awareness or actuator are needed to fulfill the operational task. Both are wireless, one has an open system, the other a closed (proprietary) communication protocol.

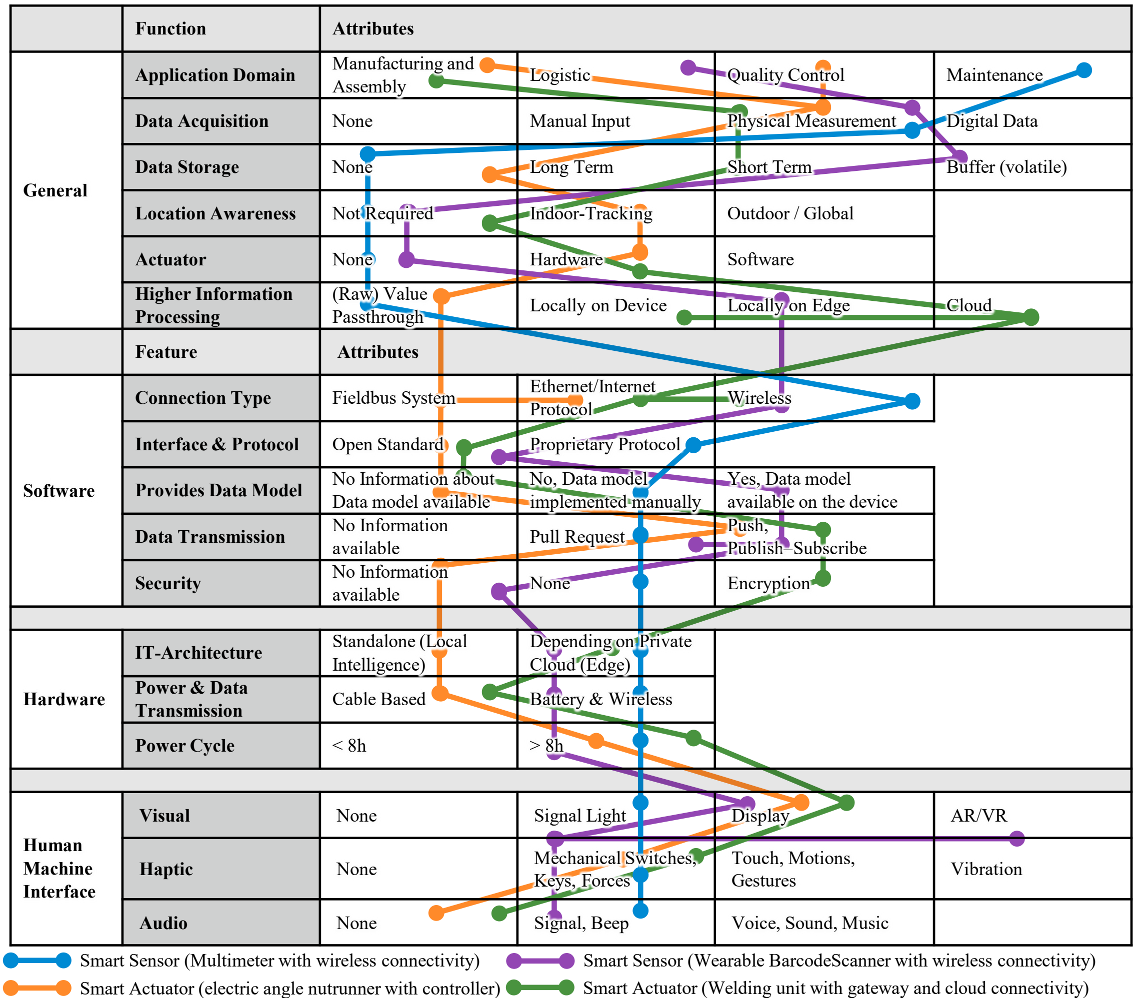

Fig. 1. Attributes of four Exemplary Smart Devices visualized using the Description Model

4.2. Smart Actuators

Also, smart actuators were analyzed using the description model. Two specific devices were analyzed. The first system consisted of a bundle of a torque tool and the wireless receiver station. The torque tool was the *ABETT STR61-50-10* [32] and the wireless receiver station the *Power focus 6000* [33] both by Atlas Copco. Its attributes are depicted in orange in Figure 1. Data acquisition is performed after the operation of the actuator is finished. In this case, the torque value of the tightened screw/nut is acquired.

The second smart actuator is a smart connected welding equipment. Its attributes are depicted in green in Figure 1. The specific equipment described is by *Lorch Schweißtechnik GmbH* [34]. The device received the program from the platform and integrated logic to execute the program.

For both devices no storage is required, due to immediate data flow. The IIoT-platform sends data to the device (parameters settings, program ID, etc.), subsequently the operation takes place and the data payload including the measured torque value is immediately transferred to the platform. The device is only usable with an active connection to the IoT-platform. The workflow demands an active connection to and from the platform, data exchange to the device from the platform is required before the process starts and data exchange from the device to the platform is occurring right after the process is finished. The devices can be enabled and disabled from the platform to ensure the correct program for a specific assembly step and to avoid misuse.

5. Discussion and Conclusion

We established that smart, connected devices have found their way on the manufacturing shop floors. They represent a tremendous opportunity to improve operations and gain valuable data-driven insights. However, as a comparably new technology, the application cases and requirements for said applications cases are not understood across the range of potential users. In this paper, we address this gap by developing a description model for smart devices. Within the development process, we identified various features and functions as well as described a range of distinguishable attributes. To showcase the value of the description model, we characterized four exemplary smart, connected devices into functions and features using the developed model. The developed description model can be used to both plan the introduction of and to evaluate smart, connected devices for different use cases.

While the presented model is a step forward to address the pertaining gap, there are several venues that must be addressed moving forward, including a typology that classifies the breadth of available (and newly introduced) smart, connected devices into common type classes. Furthermore, an investigation into a systematic procurement procedure based on categories and cost can be developed based on the classification can be built onto the presented description model. This would be beneficial for both large companies as well as SMEs. Additional industrial use cases are also encouraged to provide insights in the requirements of industrial users.

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