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Self-describing connected components for live information access within production systems

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Abstract

Access to data from components in production systems is potentially an enabler for various data-based approaches. This paper presents a practical approach to transform mechanical components into self-describing cyber-physical systems connected within a local network. The requirements for typical use cases are analysed and a modular cyber-physical connector is proposed. The data is collected by a central OPC UA client and fed into a web-based visualisation, so that it is easily accessible for operators, maintenance staff, and other stakeholders. The approach is illustrated for components with two different levels of complexity.

Keywords: Production; automation; cyber-physical system; commissioning; maintenance

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1. Introduction

To meet increasing customer needs in terms of product quality and fast delivery, flexibility and adaptability are among the most important success factors in modern production [1, 2]. In this context Industry 4.0 plays a decisive role as an enabler for manufacturing companies [3]. Adaptive, self-optimizing production systems represent the highest degree of maturity in this area [4]. Data collection and communication is a core driver of these innovations in smart factories. [5]

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Capturing and recording the relevant data represents the foundation of any data-based approach. Additionally, information about components is required for commissioning, setup, operation and maintenance. However, many factories collect little to no data on the level of individual components in production systems.

Reference architectures and guidelines for the implementation of Industry 4.0 exist and many promising use cases have been shown in industrial production. Connected and self-describing components can be seen as playing an essential role in "cyberising the physical" in order to gather the data necessary for wide-ranging digital functions. However, the state of the art lacks a practical, open and neutral approach towards integrating mechanical components in the connected world and gaining live information from these components. This contribution aims to illustrate such an approach.

1.1. Reference architectures for Industry 4.0

Suitable guidelines in the form of reference architectures support the development and classification of Industry 4.0 applications. They handle comprehensive requirements, such as connectivity, device management, data management, scalability and security forming supersets containing functionalities as well as information structures and mechanisms [6]. The reference architecture model Industry 4.0 (RAMI 4.0) ranks among the most important and most comprehensive elements to systematically classify and refine Industry 4.0 technologies. RAMI 4.0 is designed as a three-dimensional structure covering the main aspects of Industry 4.0. Horizontal localization takes place along a Life Cycle Value Stream and Hierarchy Levels. On the Life Cycle Value Stream axis, assets have multiple positions. Every asset has type-specific as well as instance-specific data. Type-specific data refers to the general product data, uniform for a product series [7]. Instance-specific data, on the other hand, represents the properties of each individual instance, which are mostly created in production and can therefore be unique for every single manufactured component [7]. Regarding the hierarchy level ranging from the product up to the connected world, self-describing components are assigned to the lower area of field devices. RAMI 4.0 defines an administration shell representing a standardized interface between one or multiple assets and Industry 4.0 communication. The administration shell represents the digital part of the Industry 4.0 component, whereas the real part is represented by the asset. [8]

1.2. Achieving business benefits through data acquisition and processing

Anderl et al. developed a guideline to support the elaboration and rapid introduction of business models for Industry 4.0, which ranges from basic preparation through a phase of analysis and creativity up to the evaluation and implementation of the developed business models [9]. A toolbox combining Industry 4.0 application levels and production-related technical applications serves as a key element. The toolbox supports in classifying the company's fields of expertise and, based on the results, in identifying further potentials [9].

Cyber-physical systems (CPS), consisting of physical systems enhanced by digital data and services, are a central element in the development of connected manufacturing systems. In line with the Industry 4.0 maturity levels mentioned above, Monostori et al. define maturity levels for cyber-physical systems (CPS) ranging from basics up to self-optimizing, with the first level comprising the structure and organization of the CPS and the upper four describing its level of intelligence. [2, 10]

Lee et al. define an architecture for the implementation of Industry 4.0-based manufacturing systems consisting of five layers, of which smart connection is the base level. Smart connection describes the required attributes to implement CPS applications und comprises capabilities in the areas of plug and play solutions, tether-free data communication and the selection of proper sensors. Consequently, these smart connection capabilities form the necessary foundation for live information access within production systems [11]. In addition to Lee's technical structure, there are more process-oriented approaches, such as the six-phase CRISP model focused on a business-oriented data mining process [12].

All these models have in common that the collection of data in production systems is a fundamental step towards achieving benefits in a manufacturing business. Before considering a practical implementation, use cases must be selected based on the existing deficits in production systems.

1.3. Wide-ranging use cases in production systems

Paper documents are still a widespread communication medium in manufacturing, especially in the field of machine tools and their components. Dosch et al. present an approach to store data on an RFID transponder attached to the component. The approach replaces the manual input of instance-specific data, making the commissioning process faster and less error-prone. Dosch et al. apply their approach to a ball screw drive. [7]

Applications within the project "Secure Plug-and-Work" also include lightweight robots [13], industrial washing machines, a tool magazine and the spindle of a machining centre, thus showing the approach to be applicable to many different use cases [14]. Wang et al. cite further examples, such as automatically generated machining process plans based on an analysis of real-time status, availability, and capability of production machines [15].

2. Design of self-describing connected components

This paper presents a practical approach to enhance mechanical components in production systems, turning them into self-describing and connected cyber physical systems. This is achieved by adding a hardware system to the component to fulfil the role of a "cyber-physical connector". The connector carries the component's self-description, including static type and instance information as well as live information acquired locally from sensors. The information is made available within a local network, allowing access using workplace PCs as well as handheld devices. The authors propose a design method for connected components with four steps: use case definition, requirements analysis, technology selection, system design.

2.1. Use case definition

Before designing cyber-physical systems based on components, the existing production system should be analysed. Based on the current development stage and the expected benefits from Industry 4.0 developments, use cases for the implementation of self-describing connected components can be defined.

This paper focuses on mechanical components for which potentially high benefits have been identified from improving the following application levels (as described by Anderl et al. [9]):

- Data storage and information access (up to the stage "Data storage with autonomous information exchange")
- Man-machine interfaces (up to the development stage "Use of mobile user interfaces")

The expected benefits of the added connectivity should be defined in order to adjust the requirements for the connected self-describing component.

2.2. Requirements analysis

Once the use case has been defined in terms of expected benefits and required data, the requirements for the cyber-physical system can be analysed. Categories are defined and typical requirements for the selected use case are shown in Table 1.

The component description can be divided into type information and instance information. The type information may be an indicator for the adequacy of the component for given tasks whereas instance information consists of an identifier (e.g. a serial number) and optionally individual properties such as deviations due to the production of the component.

Live information can be sourced from existing field devices or sensors. In both cases the interface with the data source must be defined in the following terms:

- Signal type, e.g. analogue current, analogue voltage, digital
- Signal levels
- Sampling frequency and resolution
- Communication protocol if applicable (e.g. IO-Link)
- Power supply to the sensor

Table 1. Requirements for the enhancement of typical mechanical components in a production system.

Category	Typical requirements
Static data	Type: manufacturer, model or drawing number, geometrical information, nominal load
	Instance: serial number, individual data from the component's manufacturing process
Dynamic data	Sensor data for condition monitoring and/or process monitoring (sampling rate up to 20 kHz)
	Data from existing field devices (e.g. control unit)
Data transmission	No hard real-time requirements, limited bandwidth available for communication.
Environment	Exposure to oil, water, cooling fluids and metal chips require a sealed case (e.g. IP67) and appropriate connectors (e.g. M8 or M12).
Energy supply	Input: 24V DC. Required output depending on sensor type.

Depending on the use case, the acquired data can be stored locally, transmitted to other devices or the component may react locally based on the data. In this paper, we focus on use cases in which the data is to be transmitted to other devices for visualisation.

2.3. Technology selection

In order to produce a solution that is independent of individual software and device providers, it is recommended to use open and neutral standards for formatting and transmitting data. In this contribution the combination of *AutomationML* and *OPC UA* is used, as proposed by Schleipen et al. [16]. AutomationML, a semantic format based on XML, is used here for the static description of the component. OPC UA is a standard for platform-independent communication within production systems. An OPC UA server running on the cyber-physical component is used to make the component data available within a local TCP/IP network. Thus employees can use an OPC UA client installed on a handheld device or a desktop computer to directly access and visualise the data.

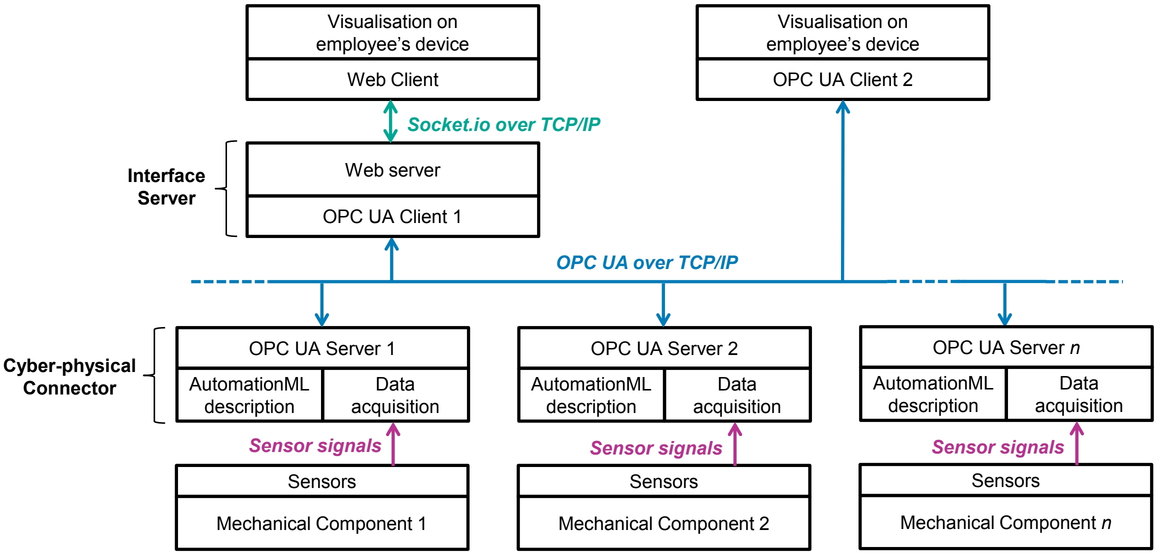


Fig. 1. Proposed system architecture for live access to component information

The OPC UA server is initially filled with static data from the AutomationML description of the component. Additionally, the live data acquired from sensors or other field devices is added to the OPC UA server and refreshed constantly. To make the data accessible through devices that do not have an OPC UA client, an interface server is set up that collects the data from several cyber-physical systems via OPC UA and represents it in a web page. Thus the visualisation requires only a standard web browser. The data is transmitted from the web server to the device using the JavaScript library *Socket.io*. The resulting communication architecture, including an interface server and several cyber-physical connectors, is shown in Fig. 1.

2.4. Prototypical design of a cyber-physical connector

A prototypical connector is designed to enable data acquisition, processing and transmission, thus implementing the administration shell as defined in RAMI 4.0. A modular architecture is chosen to enable the adjustment to the requirements of individual use cases. The connector consists of the following modules (Fig. 2):

1. DC power supply with an input voltage of 24 V enabling integration in typical automation systems
2. Sensor power supply and signal pre-processing (amplification, level shift, …)
3. Analogue-digital converter (ADC) if analogue sensors are required
4. Data processing and transmission

The modules 3 and 4 are implemented using standard circuit boards. Here module 4 is a Raspberry Pi that saves the information from local data sources and combines it with the static description in an OPC UA server. The ADC is chosen depending on the requirements described in section 2.2, especially the number of channels, sampling frequency and resolution.

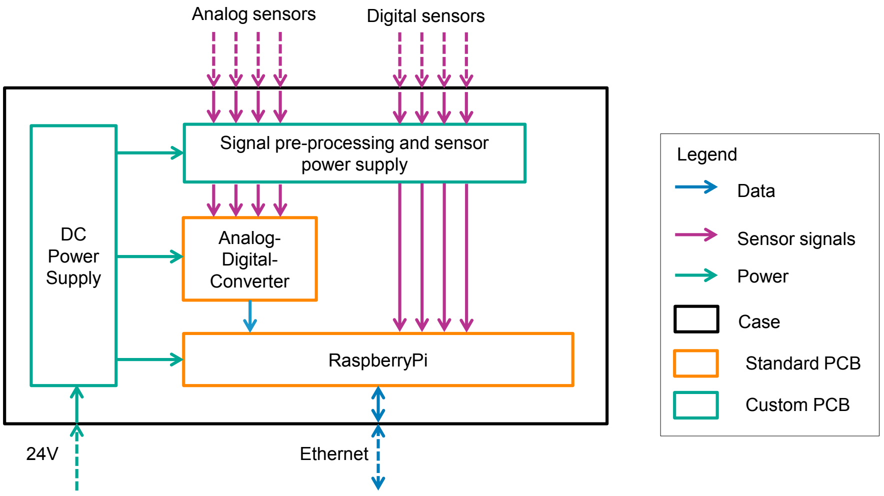


Fig. 2. Hardware architecture of the proposed cyber-physical connector for mechanical components

3. Application to practical use cases

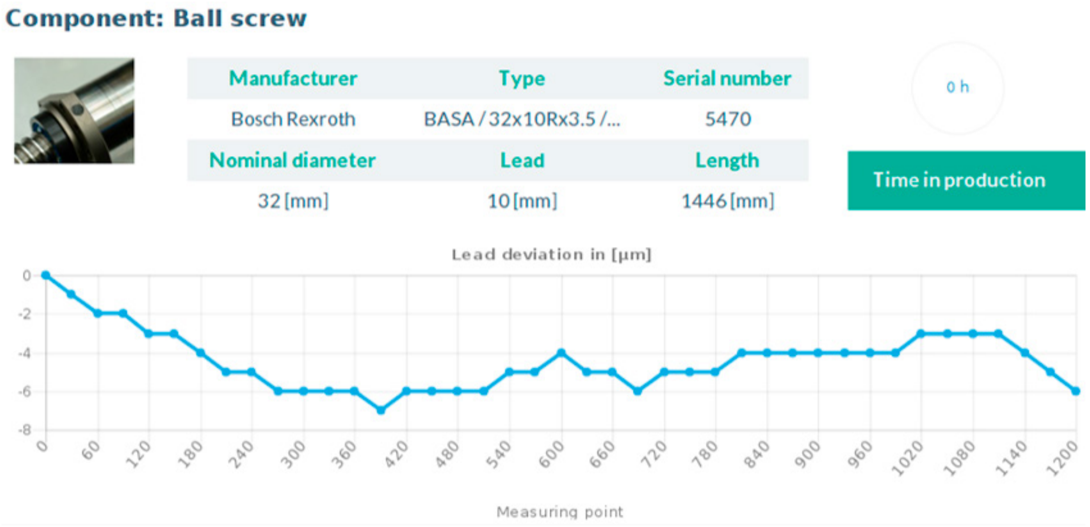
In this section the approach and the modular connector described above are illustrated in two use cases with different levels of Industry 4.0 functionality.

3.1. Use Case 1: Information access for commissioning and maintenance

Ball screws are used to drive linear feed axes in machine tools and other applications. Ball screws are especially defined by their pitch. The pitch is subject to variations due to the manufacturing process. In order to achieve a high positioning accuracy, the pitch errors must be compensated by the machine control unit. The type and instance information is relevant for the commissioning of the machine tool. This component information can be saved to an RFID chip embedded in the component, as described by Dosch et al. However a separate unit is still required to read the information from the chip and visualise it or transmit it to the control unit. [7]

The approach presented in section 2 is applied to the collection, transmission and visualisation of the information saved to the RFID chip mentioned by Dosch et al. Due to harsh conditions and the lack of available space, the connector is not placed directly on the component. Instead a single connector is used to collect the information from the ball screws for all feed axes in the machine. Using an RFID reader connected to the connector, the information is collected from each ball screw during the initial assembly of the machine.

In this use case no analogue sensors are used, thus no ADC is required. Only an RS232 interface is necessary for the RFID reader. The connector is connected to the machine control unit and other components of the machine within a local network. The information for the compensation of positioning errors can be transmitted to the machine control unit via OPC UA, enabling the automated creation of the required compensation tables. When a ball screw is replaced during the life cycle of the machine, information such as the operation time with the component can be written on the component and returned to the component manufacturer. Additionally a web-based overview of components in the machine is created using an interface server as described above. Maintenance workers can easily view the components of a machine and their status, as shown for a ball screw in Fig. 3.



Component: Ball screw

Manufacturer	Type	Serial number
Bosch Rexroth	BASA / 32x10Rx3.5 /...	5470
Nominal diameter	**Lead**	**Length**
32 [mm]	10 [mm]	1446 [mm]

Fig. 3. Web-based visualisation of component information for a ball screw.

3.2. Use Case 2: Additional monitoring functions in a machining centre

In machining centres, components such as ball screws, guide rails and spindles show potential for additional monitoring functions based on integrated sensors. In order to enable a retrofit of these additional functions without affecting the basic function of existing machining centres, a communication architecture is required that is independent from the original control unit. The approach described above is well suited to this application, as it accommodates various signal types and does not rely on any specific pre-existing control system.

Acceleration, deformation and temperature are relevant physical quantities for monitoring the condition of mechanical components, as exemplified by Spohrer et al. for ball screws [17]. The measurement of vibration through acceleration sensors requires the acquisition of analogue signals with a high sampling frequency, therefore a fast ADC is required in the connector. ADS1278 from Texas Instruments is chosen for its ability to acquire up to 144000 samples per second with a bandwidth of 70 kHz. It is set up to communicate with a Raspberry Pi via SPI.

4. Conclusion

Based on an analysis of typical requirements for mechanical components in production systems, a modular cyber-physical connector is proposed. The connector carries a self-description in AutomationML and combines this information with local data sources such as sensors. It enables access to a live description of the component via OPC UA, thus establishing a basis for data collection from components in productions systems.

The information can either be automatically taken into account by a connected control unit or consulted directly by maintenance staff equipped with a device running an OPC UA client. An interface server further facilitates the visualisation of component information by all stakeholders in the factory, who can then access the information on any device equipped with a web browser.

Currently 10 prototypes of the connector are being installed in order to gather data in an industry partner's factory. An important preliminary arrangement for practical implementation on the shop floor consisted in setting up a separate virtual local network within the company, in order to integrate the connectors into the existing IT infrastructure.

Further work could focus on reducing the size and cost of the connector, gaining autonomy by powering the connector with batteries, and using the data collected from components to monitor the production process. Another interesting addition would the ability for the connector to react locally to the collected data, for example by stopping a machine or warning the operator.

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