Communication Protocol Application for Enhanced Connectivity of Sensors, Machines and Systems in Additive Manufacturing and Production Networks

Cordula Czwick(✉), Stefan Kugler, Jennifer Greven, and Reiner Anderl

Department of Computer Integrated Design, TU Darmstadt, Otto-Berndt-Str. 2, 64287 Darmstadt, Germany
czwick@dik.tu-darmstadt.de

Abstract. The connection between sensors, systems and machines in the production environment enables new concepts to increase quality or flexibility. Integrated sensors can measure machine performance parameters. The measurements serve for monitoring of process stability and quality or for affecting production planning through a new agile routing. To realize the new concepts, data needs to be transmitted from the sensors to a data management system, where the collected data can be analyzed and stored. The communication between sensors, machines and systems is a central aspect and, therefore, a big challenge. There exist different protocols to enable communication, but choosing the proper protocol for a special use case is difficult. There does not exist a method that supports the choice of the protocol depending on the initial situation and the user's preferences. Therefore, the aim of this paper is the development and implementation of a method that supports the selection of a communication protocol in an Industrie 4.0 surrounding for enhanced connectivity between sensors, systems and machines in the production depending on the individual initial situation and the personal preferences. After a short motivation and state of the art, two use cases are described and the development of the concept is explained. The following implementation shows the realization of the concept and enables the use of the concept on the two use cases. The paper ends with a conclusion and outlook.

Keywords: Industrie 4.0 · Digitalization · Communication · OPC UA · MQTT · Production network · Project ArePron

1 Introduction

Developments in the field of digitalization enable new business models and help to enhance products in the whole lifecycle. One technical requirement for Industrie 4.0 is the clear identification of all instances. A well-defined description helps to identify all components, machines and systems. Another technical requirement is the localization, which describes the precise and actual location of a certain component. For the communication between machines and components, the third technical requirement is very

Published by Springer Nature Switzerland AG 2019
C. Fortin et al. (Eds.): PLM 2019, IFIP AICT 565, pp. 136–145, 2019.
https://doi.org/10.1007/978-3-030-42250-9_13

important. This is the addressing, which helps to control devices through the mapping of an individual address for connection and communication. [1]

Communication between components, machines and systems enables the vision of a flexible and autonomous production especially for individualized products or small lot sizes [2, 3]. In this paper, the requirements to enable an adequate communication are investigated and described. The aim of this paper is the development of a method, which helps to choose a proper communication protocol for the connection of sensors, machines and systems in the production environment. Until now, a user-friendly method for the selection of a communication protocol in Industrie 4.0 does not exist.

For the communication in an Industrie 4.0 surrounding, several protocols exist as an option. The mostly known options are OPC UA, MQTT and DDS. The protocols enable the data flow between sensors, machines and systems and therefore the connection between all devices in the production environment. This paper compares the three protocols OPC UA, MQTT and DDS and analyses the advantages and disadvantages of each possibility. OPC UA stands for "Open Platform Communications Unified Architecture" and is a standardized communication protocol for machine-to-machine communication. The strengths of the protocol are the high security standard through an additional message encryption and authentication and the semantic transmission of data or even complex data [4–6]. The protocol MQTT (MQ Telemetry Transport) is even suitable for devices with limited resources and works well with instable connections and nets [7, 8]. DDS or "Data Distribution Service" is a communication protocol developed by the Object Management Group in 2004 and features a decentral structure with an opportunity of data filtering [9, 10]. Section 3 deals with a detailed evaluation of the three protocols. Based on the analysis of the three protocols, the resulting information gives an advice, which protocol shall be selected for communication. Therefore, a concept is created and presented in the next parts of the paper.

2 Uses Cases for Additive Manufacturing and Production Networks

This section deals with the use cases and their usage. There exist two use cases, which, on the one hand, support the motivation for the concept development, and, on the other hand, serve for implementation and validation of the theoretical concept. The use cases are real existing systems with different characteristics and requirements, which are described in the following.

Use Case "Additive Manufacturing Lifecycle"

The Additive Manufacturing (AM) lifecycle for fused deposition modeling (FDM) comprises the different lifecycle phases starting with the material production. A material extruder represents the material production phase. Granulate material is transformed into filament. The next phase is the product development phase. After designing the part, the machine preparation takes place. A small FDM printer represents the preparation and printing process. After the product development phase, the product distribution and product use phase follow. The last phase is the product end of life. A shredder represents the product recycling phase and produces new granulate material of old components [11]. To control the production process and the quality of the printed part, several sensors are integrated into the machines. The measurements of the sensors and the information of the machine control are collected in a database [12]. To transfer data, a proper communication protocol is needed. Requirements on the protocol are in this use case: fast and reliable transmission of data, simple implementation, good expandability of new machines or sensors and reliable function with instable nets.

Use Case “Production Network in ArePron Project”

The name ArePron stands for agile resource efficient production network. The project is approved by the Hessian Ministry of Economics, Energy, Transport and Regional Development (HMWEVL) and financed by the European Regional Development Fund (ERDF) and the Hessian Ministry [13]. It started in January 2018 and ends in December 2020. The aim is an increase of the resource efficiency of the production with the help of an agile, cross-location linking of production systems. Rules and performance indicators are created, that can lead to an increase of the resource efficiency. The collected data help to calculate the performance indicators and rules. Therefore, the resource efficiency of a manufactured part can be determined and, in the end, optimized. The improvement of the resource efficiency enables a cost reduction while the ecological footprint of the company reduces. In the work package of the Department of Computer Integrated Design, the information and communication infrastructure is developed and implemented, which enables the acquisition und usage of data. Therefore, a communication protocol for machine and systems communication is needed. This protocol has to fulfill standards of a real industrial production concerning the security and the function of the protocol. Sensors of the machines and information of the programmable logic controller need to be transferred to a database, where the defined rules and key performance indicators determine the best production route in the production network.

3 Development of a Concept for Selection of a Communication Protocol

The aim of this paper is the development of a concept that helps to choose a proper protocol to enable an Industrie 4.0 communication within machines, systems and components in a production environment. Therefore, the first step is the selection of criteria that can characterize communication and that can help to decide which protocol is suitable. The next step is the characterization of the three protocols OPC UA, MQTT and DDS. Each protocol is evaluated concerning the decision criteria. An overview summarizes all advantages and disadvantages of every protocol. The information serves as general input for the method. The next step is the concept development. The overall method and the single steps of the concept are introduced and presented. After this, the implementation and validation take place in the following section.

The concept and the method have two significant layers. The first layer proofs the technical abilities. The three protocols are analyzed concerning the strengths and weaknesses. In this layer of the method, a first request on the user takes place. The user has to insert his requirements depending on categories. The three protocols are evaluated for every category. The result of this first layer are all protocols that can satisfy the technical requirements. For this first layer, rating criteria need to be chosen and evaluated for the three protocols. The second layer of the method comprises the preferences of the user. With the help of a utility analysis, the user can bring his individual preferences into the method. For the utility analysis, the user decides the weighting of meaningful criteria. Depending on this, the method ranks the protocols and gives an advice, which protocol is suitable for the defined use case. Figure 1 presents an overview of the method.

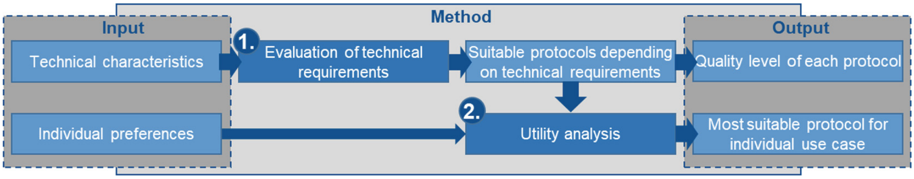

Fig. 1. Two layers of the method in an overview

To fulfill the technical requirements, rating criteria are necessary. The selection of criteria is an important first step for a meaningful method. The analysis of requirements of Industrie 4.0 helps to identify important criteria. The most important requirement of Industrie 4.0 is the vertical and horizontal integration. Vertical integration means that data is available for every authorized person or machine of every step of the process chain. Horizontal integration describes the exchange of data between individual enterprises. In terms of scalability, the connection of hundreds of devices has to be enabled. The three requirements generally count for all Industrie 4.0 activities. For the method, special requirements on the communication and especially the protocol are important. The transmission rate describes the time between an event on one device and the arrival of data on another device. Industrie 4.0 adequate transmission rates have times of few milliseconds. The real-time capability describes the awareness of the latest possible arrival time of a message at a certain device. Therefore, the real-time capability can reduce security risks. Through the independence of the protocol from the manufacturer or certain systems, the communication is possible with every system or device. Standard interfaces support an easy change of clients. An easy implementation of the protocol and a high flexibility in the structure of the protocol simplify the protocol itself and its use. A communication with the help of the internet enables a communication of devices separated by open ground. The stability ensures the function of the protocol even under poor connections or high data traffics. For the data, additional requirements exist. The requirements are a permanent availability of the data with several access facilities, a guaranty for the transmission of the data and the consistent access and output of data independent of the data type. For the devices or clients, the localization, identification and addressing are important requirements as explained in the introduction. Besides, a high flexibility enables an easy change of clients. To maintain a certain security level, only authenticated users have access to the system and the messages. A high safety level ensures a safe use without accidents even with incorrect operation [2].

The important requirements on the protocol, the clients and the data can be divided into four main groups: transmission, structure, function and security. The four groups are used as cluster for the decision criteria. The protocols OPC UA, MQTT and DDS have different strengths. The decision criteria help to point out the strengths and weaknesses. The first three questions represent the main group transmission. The transmission group deals with the latency, the real-time and the possibility to transfer complex data. A transmission faster than milliseconds works only with the protocol DDS. The protocols MQTT and DDS predict the maximum time when the message arrives the recipient at the latest. Complex data can only be sent with the protocol OPC UA. For the main group structure, the general structure with or without a broker (centralized or decentralized) and the initial knowledge of the type and content of the data are important topics. The protocols OPC UA and MQTT are suitable for the transmission even if it the data is not known and filtered initially. Only the protocol DDS supports a decentralized structure without a broker. The main group security deals with the encryption of the message and the authentication of the devices. The protocol OPC UA enables an encryption of the messages additional to the encryption of the connection. OPC UA and MQTT offer the possibility to authenticate devices. The forth group is the function that includes encoding and the quality of the connection in the network. The protocols DDS and OPC UA enable the encoding that enables a faster transmission. With a changing connection, MQTT can be used. Figure 2 shows the decision criteria separated into the four groups and the evaluation of the three protocols OPC UA, MQTT and DDS in an overview.

Categories	User questions for the decision criteria	Evaluation if	OPC UA	MQTT	DDS
Transmission	Must it be possible to predict the maximum time when the message will reach the recipient at the latest?	yes	x	✔	✔
	Does the transmission have to be faster than in ms-range?	yes	x	x	✔
	Does the protocol also have to be able to transfer complex data such as control data?	yes	✔	x	x
Structure	Is it not known at the time the protocol is set up which data must be transmitted and / or should the content of the data be filtered?	yes	✔	✔	x
	Should the data be transferred via a decentralized structure (no central broker)?	yes	x	x	✔
Security	Should the message be encrypted in addition to the connection encryption?	yes	✔	x	x
	Should it be possible to authenticate devices?	yes	✔	✔	x
Function	Do the data have to be encoded for example for a faster transmission of large data packages?	yes	✔	x	✔
	Is there not always a constant connection in the network?	yes	x	✔	x

Fig. 2. Decision criteria with an evaluation of the three protocols

Depending on the necessary technical requirements, a ranking of the protocols takes place. If the protocol fulfills all requirements, the protocol reaches the first quality level with nine points. For the second quality level, the protocol achieves seven or eight points.

Protocols of the first or second quality level satisfy the technical requirements. In the next layer of the method, only the protocols of this quality levels are considered.

The second layer deals with the utility analysis. With the help of the utility analysis, the user can place his individual preferences. Through the analysis of the user stories, four important categories result. The first category is the simple implementation. The time of becoming acquainted with the protocol shall not exceed the time of the implementation. Especially in traditional enterprises, a simple and adequate implementation motivates a project for digitalization. The next category is the fast transmission of the data. On the one hand, a fast transmission saves time and in the end money. Fast transmission enables an optimization of routing or machine scheduling. Therefore, a fast transmission bears new business cases in an enterprise. On the other hand, a fast transmission supports a long-term use of the protocol. With the increasing digitalization, transmission speeds and the use of data increase as well. Choosing a protocol with a fast transmission now helps to keep the actuality of the technical state for a longer time. The following category is the semantical data description. This can be important for the user, because it enables a simple and compact read-out of the data. The last category addresses the connection of devices. If the connection shall only take place between sensors, the user can put his focus on this. After the request of the preferences, the method presents the most suitable protocol to the user. In case of several options, the method asks for the country of the use case. The place of implementation is an interesting factor because the use of the protocols differs strongly between the countries. If the protocol is often used in a country or region, there exists a better infrastructure for costumer support. After considering all aspects of the technical requirements and the individual preferences, the best protocol for the user's case is presented in the end.

4 Implementation and Application on the Use Cases

The implementation of the method tend to an easy and efficient use. Therefore, requirements are a self-explanatory handling and a clear view. The use of the implemented method shall be possible directly without a long training. Besides, the implemented method shall be operated without an additional software with the common operating systems. Based on the requirements, the software Delphi is chosen for the implementation. Delphi works with the programming language Pascal and enables the preparation of clear user interfaces.

In a first step, the user interface is developed through drag and drop. The choice of objects is limited on a fixed number, but still suitable for a productive implementation. Just as the concept of the method, the implementation is separated into two parts. The first part serves for the evaluation of the technical feasibility. For every decision criterion, the necessity is determined. The user can answer with a "yes" or a "no" for every decision criterion. If a decision criterion is important, the user can mark the "mandatory" button. This decision criterion cannot be neglected in the choice. The protocol has to fulfill this decision criterion otherwise the protocol is suspended. After the evaluation, the user presses the "calculate" button. A direct evaluation gives feedback and shows the ranking of the three protocols OPC UA, MQTT and DDS depending on the user's input. Besides the quality level and the achieved quality points, the evaluation tells the missing properties for every protocol. This gives a first information to the user how many protocols can be considered in the second part of the method. If all protocols show a negative rating, the user can either reconsider his input or interrupt the method directly. The user pushes the “next” button to reach the utility analysis. The user inserts his preferences with the help of percentages. If the sum of the four inputs does not result in 100%, the method adapts the weighting factors for intern calculation. After pushing the “calculate” button, the method shows the results of the utility analysis for the three protocols. If the difference between the values of the protocols is small (<10 points) a new input mask appears. The user chooses the county where the project takes place. After pushing the “final decision” button, the method gives an advice which protocol is the most suitable option for the descripted use case. Besides the recommendation of a protocol, all properties that are not fulfilled are mentioned. The advised protocols match the technical requirements, if not, they are not included in the second part of the method.

For an application of the method, the use cases are used. Section 2 describes the two use cases “Additive Manufacturing Lifecycle” and “Production Network in ArePron Project”. Use case one “Additive Manufacturing Lifecycle” has technical requirements on the transmission and the security. Figure 3 shows an extract of the method.

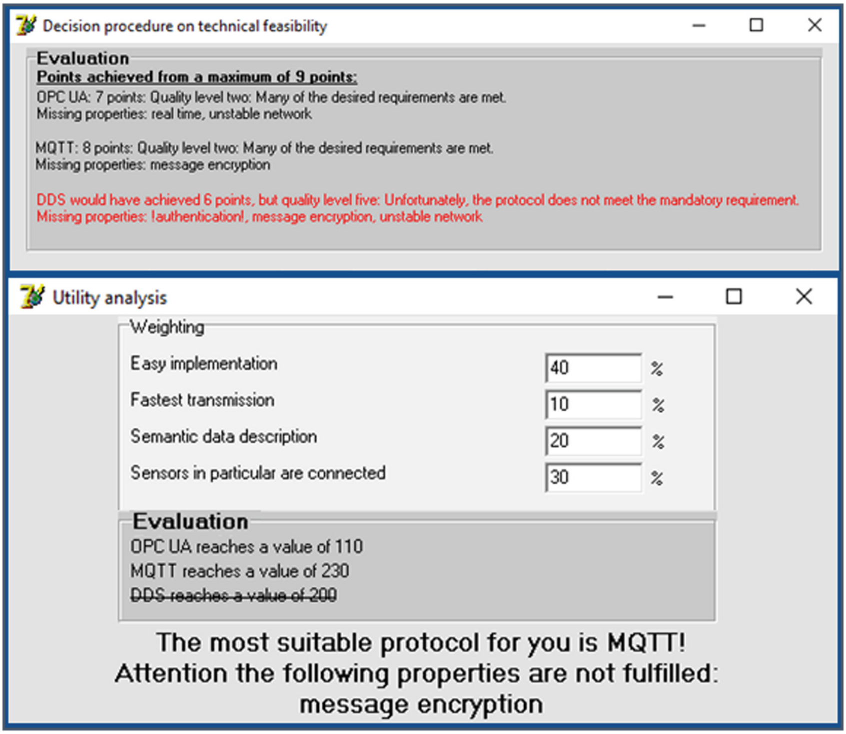

Fig. 3. User interface of the method used for the additive manufacturing lifecycle

In this case, the maximum time when the message will reach the recipient needs to be predictable. Besides, the message has to be encrypted additionally to the connection encryption. The authentication of the devices is mandatory. Based on the mentioned technical requirements, the method recommends OPC UA and MQTT with the quality level two. OPC UA does not offer real time. MQTT misses the message encryption. In the next step, the utility analysis takes place for the final decision. For the "Additive Manufacturing Lifecycle" an easy implementation is most important and assessed with 40%. Most of the devices are sensors. Therefore, this criterion is weighted with 30%. The semantic data description is rated with 20%, the fast transmission is assessed with the last 10%. Based on this rating, the method recommends the use of the protocol MQTT with the hint of the missing functionality of message encryption.

Use case two "Production Network in ArePron Project" has technical requirements on the categories transmission, structure and security. To plan and determine the agile routing in the production, the maximum time of the transmission has to be predictable. Besides, the protocol has to be able to transfer complex data like the control data for the machines. In the actual state of the project, doubts exist concerning the collected data and a potential sorting of the raw data. The data is used for determining the ecological efficiency of a product and adapt the agile routing. There do not exist a key performance indicator that considers the influences of the digitalization in the economic efficiency of products. Therefore, this indicator is developed in the project and this is why the final data is not indicated yet. The ArePron project is a funded Hessian transfer project. Therefore, all results have to be transferable to small and medium-sized enterprises. For enterprises, security of the data is the most important point to keep the business secrets and therefore the competitiveness. Hence, the authentication of the devices and the additional encryption of the messages are mandatory. With the mentioned technical requirements, the method advices OPC UA for the project. MQTT and DDS do not meet the mandatory requirements concerning the security. Therefore, MQTT and DDS are eliminated as alternatives. Figure 4 presents the user interfaces for the evaluation for the second use case.

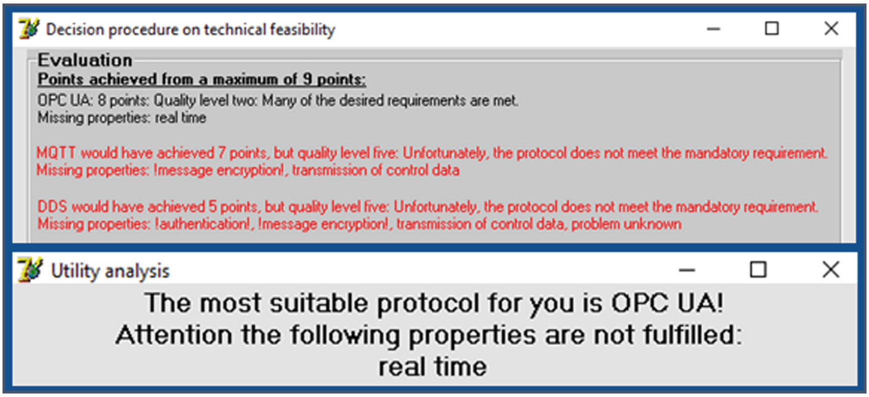

Fig. 4. User interface of the method for the production network in ArePron

In this case, the utility analysis is overleaped and the method is presenting the most suitable protocol directly. For the second use case, the suitable protocol is OPC UA.

The use cases evaluate the function of the developed method. The advised protocols match with the strengths and weaknesses that are described in the beginning of the paper. Therefore, the method serves as assistance in the selection process of a protocol for communication in Industrie 4.0 environments.

5 Outlook and Conclusion

The paper presents the development of a method for the selection of a communication protocol depending on technical and individual requirements. Therefore, in a first step, requirements of Industrie 4.0 and the protocols OPC UA, MQTT and DDS for communication are described in an overview. The next section deals with the two use cases. In the use case "Additive Manufacturing Lifecycle", mostly sensors need to be connected to a data management system. For this research project, an easy implementation and a reliable function in case of inconstant connection is important. The use case "Production Network in ArePron Project" deals with the acquisition of production data to determine a new agile resource efficient routing. Especially the requirements on the security are mandatory, because the project pictures a real production environment of a small or medium-sized enterprise. The following section describes the development of the method. The method consists of two layers. The first layer is the evaluation of the technical requirements. The user answers questions of the four categories transmission, structure, security and function. With the answers, the technical suitability of the three protocols is evaluated. The second layer consist of a utility analysis. The user can weight four factors. Based on the user's preferences the most suitable protocol is displayed. For implementation, the software Delphi with programming language Pascal is chosen. The two use cases enable the application and validation of the method. For the first use case, the protocol MQTT is recommended, for the second use case the method advises the protocol OPC UA. This shows that for different applications different protocols are needed. In the next step, a validation of the real use of the chosen protocol in the use cases and a feedback to the method concerning the protocol implementation and usage are necessary. Furthermore, the number of protocols in the method can be enlarged. With the help of further protocols in the selection, the requirements can be covered accurately and therefore the area of application of the method enlarges. Besides, a further development of the communication protocols is necessary to enable the flexible use and the potential combination of the different protocols.

Acknowledgements. The use case two is part of the transfer project "ArePron – agile resource efficient production network". The project is approved by the Hessian Ministry of Economics, Energy, Transport and Regional Development (HMWEVL) and financed by the European Regional Development Fund (ERDF) and the Hessian Ministry. The project is a collaboration between the Department of Computer Integrated Design, the Department of Material Flow Management and Resource Economy and the Institute of Production Management, Technology and Machine Tools. The project started in January 2018 and ends in December 2020.

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