Integration of an IoT Communication Infrastructure in Distributed Production Systems in Industry 4.0

Jiahang Chen and Jürgen Roßmann

Abstract

The term Internet of Things (IoT) denotes a communication network, where various Things are interconnected using novel scenario-specific Internet technologies and predefined customizable semantics. Industry 4.0 aims at enabling a globally networked production, with the use of IoT as a crucial concept. Since production systems tend to be technically and organizationally heterogeneous, distributed at different locations, and associated with large amounts of data, communication and information processing platforms that provide confidentiality, integrity, availability (CIA rules), access control, and privacy are needed. In this contribution, we introduce a concept for designing and operating heterogeneous and spatially distributed industrial systems with Digital Twins, connected via an IoT communication infrastructure, the Smart Systems Service Infrastructure (S3I). By demonstrating an industrial use case with our concept, it is proven that the S3I can be used as a cross-domain solution for the interconnection of devices in a distributed production scenario.

Keywords

Internet of Things • Industry 4.0 • Communication • Smart Systems Service Infrastructure

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1 Introduction

Industry 4.0 is concerned with the digital transformation of industries and is world-widely known, especially in the manufacturing sector. In this context, traditional industries are going to be combined with novel technologies such as Cyber-Physical Systems, the Internet of Things, Cloud Computing, and Big Data to enable a globally networked, personalized, and goal-oriented Smart Production [14]. The term Internet of Things (IoT), a crucial component at the forefront of Industry 4.0, aggregates various everyday objects to collect, exchange, process, and visualize data through the integration of scenario-specific Internet technologies and predefined customizable semantics to enable the situation-specific choreography in different domains.

The introduction of Industry 4.0 will inevitably lead to changes in the supply chain [2] to respond more flexibly to the adaptation of various technologies. As in the automotive industry, a car may consist of more than 30,000 different components produced from different raw materials and various manufacturing processes. In this regard, with increasing demand for transparency and flexibility in today's production systems, traditional manufacturing is confronted with the transition from a centralized, production-based manufacturing model to a distributed, small-scale, and loosely coupled model.

Distributed production [20], a new form of localized manufacturing, eliminates the need for companies to forecast demand and maintain large inventories, and also enables the flexibility to reconfigure production structures [15]. An important aspect of distributed production is interconnectivity among distributed systems and their devices. In this context, how to deal with technical and organizational heterogeneity and ensure the confidentiality, integrity, and availability (CIA rules) of communication and information processing is turning out to be a primarily concerned topic.

In this paper, we focus on distributed production systems and contribute a concept to network heterogeneous and spatially distributed production systems with Digital Twins [13], connected via the Smart Systems Service Infrastructure (S3I, depicted in Fig. 1) [3, 17]. The S3I is initially developed as an IoT communication infrastructure to interconnect and orchestrate the so-called *Forestry 4.0 Things* [3, 5, 19]. The remainder of this paper is structured as follows: Sect. 2 summarizes the state-of-art communication architectures in distributed manufacturing. A general concept including the requirements is illustrated in Sect. 3. Its implementation in a simulation-based application is introduced in Sect. 4. In Sect. 5, the paper is concluded.

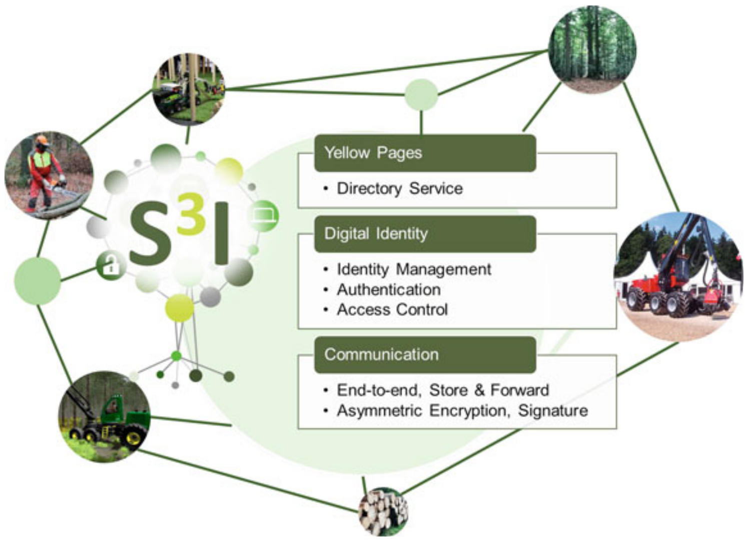

Fig. 1 The Smart Systems Service Infrastructure as IoT communication infrastructure provides various services to interconnect decentralized Forestry4.0 Things

2 State of the Art

In this section, we summarize some state-of-the-art communication architecture solutions for industrial distributed production systems.

2.1 Centralized ERP

Enterprise Resource Planning (ERP) refers to a comprehensive software solution for the central management of companies' resources. As proposed by Thomas Andre [16], the integration of an ERP system into the process flow helps the decision-making to be hierarchically broadcast from the upper levels to the lower levels, which is managed in a distributed autonomous way to dispatch the decisions explicitly to the respective executor. Similarly, George L. Kovacs contributes a web-based solution [9] for ERP systems as flow management solutions to manage scalable, multi-agent, multi-company production.

2.2 Cloud-based Solutions

Cloud computing uses IT and its associated technologies to drive the digital transformation of the manufacturing industry towards on-demand computing services. Following this structure, Xu proposes a layered architecture of a cloud manufacturing system [21]. This proposal incorporates a resource layer to deal with static and dynamic resources of software and hardware, a virtual service layer in charge of identifying manufacturing resources, a global service layer collaborated with cloud technologies, and an application layer dealing with user interactions. Rimal contributes architectural requirements [12] for cloud providers, enterprises, and cloud users, respectively. These can be summarised as general requirements for cloud system design.

2.3 AAS-based Networking

The Asset Administration Shell (AAS), a concept associated with RAMI4.0 [7] and regarded as the I4.0 equivalent of Digital Twins, can be combined with its asset (e.g. device, machine, equipment, etc.) to form a Component to represent all relevant data with a uniform interface [18]. As a middleware for Industry 4.0, Basys 4.0 is concerned with 1) decentralized connection of AASs, 2) Virtual Automation Bus [10] as an implementation of end-to-end communication, and 3) service-oriented process control. Using Basys 4.0, Antonino, et al. developed an automatic pallet transport system to bundle a high-level control and monitor of the status of the system [1]. Perzylo et al. [11] introduce a concept that adopts capability-based semantic annotations of existing information models to enrich device models aiming at the orchestration of high-level skills from the perspective of BaSys 4.0.

2.4 Summary

Despite their successful applications in various industrial fields, the reference architectures described above still have several considerable limitations and debatable aspects. Firstly, as interpreted by Sun [4], the failure rate of the implementation of ERP systems ranged from 40 up to 60%. Furthermore, ERP systems focus on interaction, mainly at the upper levels. Hence, they are not able to deal with the events triggered at the lower levels of production [16]. Besides, heterogeneity dissimilarities of production systems and lack of semantic interoperability make the interconnection even more difficult [8]. The introduction of cloud-based technology into the industry raises concerns about sensitive manufacturing information. Meanwhile, not all cloud users want to store their data in the cloud and accept the security mechanism provided by the cloud provider. The architecture of AAS-based networking covers the basic requirements for the RAMI4.0 framework, but its openness and secure nature is still a topic for globally networked production systems.

The use of the proposed concept brings various benefits to industrial distributed production systems. First, S3I combines several standard protocols to ensure the access security of everything connected to the infrastructure. S3I's distributed concept allows all Things to be managed without the need for centralized integration and without limiting the storage and management of resources centrally. In addition, S3I accommodates technical and organizational heterogeneity and ensures transparent, mutually understandable interactions through customizable semantics.

3 Concepts

Faced with the shortcomings of the current industrial communication architectures introduced in Sect. 2, we propose in this section our concept to interconnect heterogeneous and spatially distributed production systems with Digital Twins, focusing on the aspects of secured communication and interoperability by means of the proposed semantics.

3.1 Requirements

Our concept is presented under consideration of the following requirements: **Authentication** denotes that the identity of all participants in the IoT must be verified either decentrally or centrally before they are connected to the IoT. **Confidentiality** emphasizes that only the authorized users have the right to access protected resources, especially during the exchange of data. **Integrity** refers not only to the data completeness but also to the accuracy and truthfulness of the exchanged data. Data integrity can be ensured by adopting e.g. symmetric/asymmetric data encryption approach. **Heterogeneity** is related both to technical and organizational aspects originating from large and time-varying value-added networks with different actors. **Interoperability** refers to a capability of transparent interconnection between all communication participants such as Semantic Data Model [6], a common language "spoken" by all participants or a tool to depict the content of Things in the meta-level.

3.2 Digital Twin

The definition of Digital Twin varies slightly under each emphasis in different fields. In general, everyone agrees that Digital Twins are a 1-to-1 replica of the real world. In this context, Digital Twins are continuously updated during their entire life cycle through the internal and digital connection to their represented Assets. The interconnection between Digital Twins requires a capacity to extract valuable insights from large amounts of data originating from diverse devices, services, processes, systems, etc. Hence, semantic modeling, which is used to illustrate the relationships between values of data, is gradually taken into consideration and incorporated into our concept, which lets Digital Twins understand each other connected to them.

3.3 From Digital Twin to I4.0 Things

We define the combination of an asset and its Digital Twin as an Industry 4.0 Component (I4.0 Component). Together with Human-Machine Interface (HMI) and software services, they are termed *Industry 4.0 Things* (I4.0 Things), which can be seen as nodes of IoT in charge of collecting, exchanging, processing and visualizing data while being networked with others. An I4.0 Thing is globally uniquely identifiable, has predefined properties and interfaces, and supports standardized services. It can be connected to a goal-oriented Industry 4.0 System (I4.0 System) that consists of various I4.0 Things. The integration of Digital Twins in IoT enables a standardized interface for everything connected to the IoT, making Things as accessible nodes. Digital Twins can also be considered as software runtime environments that provide a virtual space for data processing and simulation.

Figure 2 illustrates a simplified Semantic Data Model of I4.0 Things in our aspect, which defines uniformly the structure as well as existing properties and callable functions provided by I4.0 Things. The data model denotes that each Thing has a unique identity managed in a central identity management service. Furthermore, each Thing can restrict the access from others and define the access policy, i.e. who can access it with given permissions. It also exposes endpoints to the external world, through which Things can be reached to provide values (via Property) and service functions (via Functionality). Each Thing can be partitioned into smaller but independent Things (via hasSubThings), like a car is composed of an engine, four tires, etc. An engine can be modeled as an independent Subthing of a car and provides

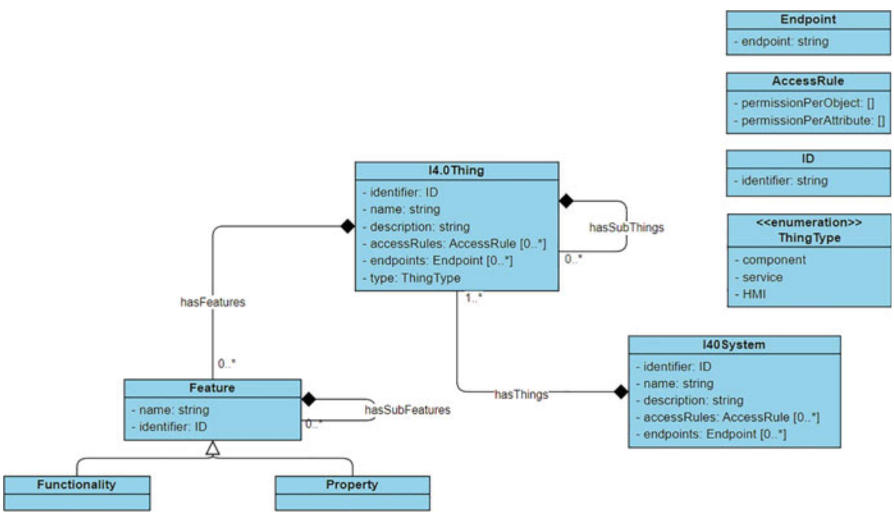

Fig. 2 UML class diagram illustrates the Semantic Data Model applied to model and implement Industry 4.0 Things

e.g. rpm value and temperature. Furthermore, diverse I4.0 Things can be associated to enable the situation-specific choreography, comprising an I4.0 System.

3.4 Platform

As I4.0 Things are defined as "worldwide identifiable participants" [18] able to communicate and could be distributed over large areas, a central infrastructure with a few essential software services is required to realize a decentralized interconnection of those Things. These services facilitate that I4.0 Things are able to authenticate themselves, store and re-find their properties and features in a database, and end-to-end compliantly communicate with each other considering the given permissions. The S3I as an IoT infrastructure provides directory service (via S3I Directory), OAuth 2.0 authentication (via S3I Identity Provider), optional message-based asynchronous communication (via S3I Broker using AMQP), and optional cloud storage (via S3I Repository). The use of S3I is domain-independent and meets the shortcomings enumerated in Sect. 2.4 and requirements listed in Sect. 3.1.

4 Application

In this section, we implement the concept mentioned above in a simulation-based scenario to demonstrate the communication between distributed production systems, including their I4.0 components, services, and HMIs.

The use of the S3I enables different factories that are networked over large areas an integrated high-level communication. Meanwhile, the interaction at the system level is centrally managed by the S3I. The example in Fig. 3 illustrates how the I4.0 Things are networked with the S3I. In our application, Factory n attempts to get the current production status of Factory 1, see Fig. 4. All the Things appearing in this scenario are modeled as I4.0 Things using the semantic model presented in Sect. 3.4. As an example, Fig. 5 depicts the meta information of Factory 1 in JSON format. Using the standardized REST API of the S3I Directory, Factory n retrieves the endpoint and the interface provided by Factory 1 with a valid access token issued by the S3I Identity Provider. Subsequently, Factory n completes an encrypted and signed message including concrete request content and sends it to Factory 1 via S3I Broker. Because Factory n has obtained the access right to Factory 1 previously, Factory 1 is allowed to give an appropriate response. As a result, Factory n obtains the status of the field devices in Factory 1 via S3I Broker as well.

To sum up, the participants in the network are not required to be aware of how other Things are implemented, how the internal logic works, how communication proceeds and which programming language is used. They only need the corresponding access rights to the interfaces to acquire appropriate information and conduct service functions because they

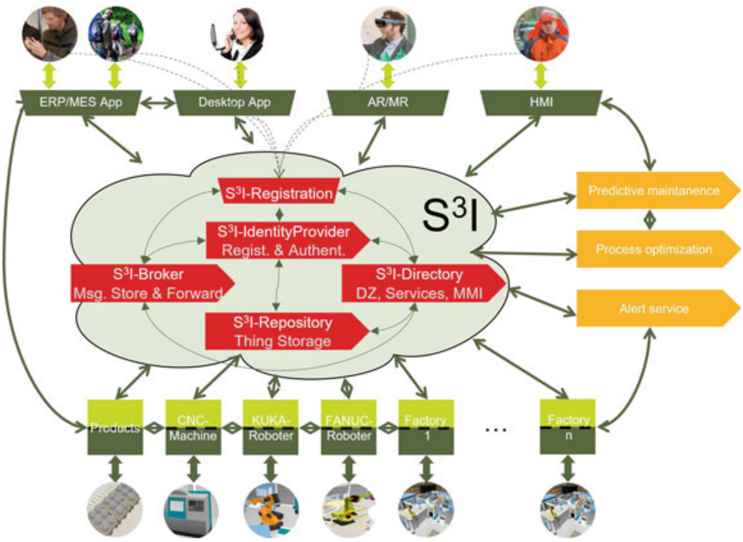

Fig. 3 Various Industry 4.0 Things in Distributed production systems interconnect with each other using the S3I and its provided services

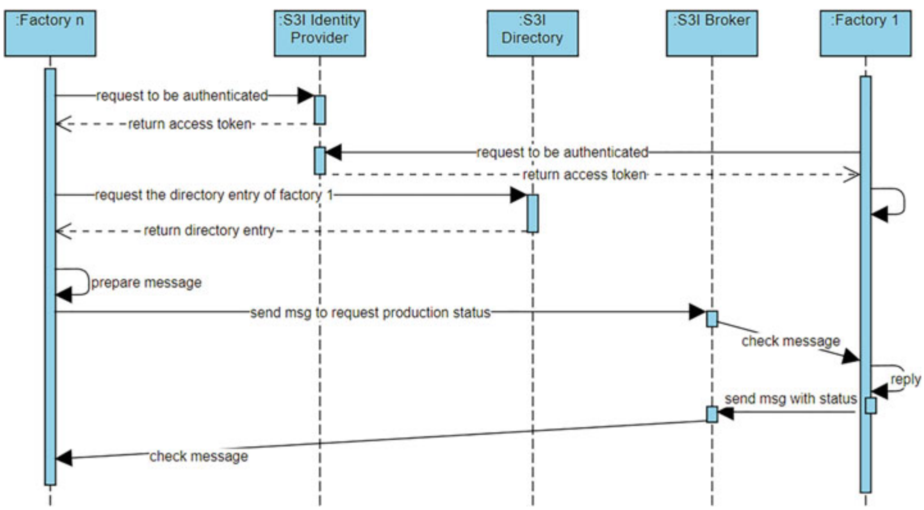

Fig. 4 Sequence diagram illustrates how Factory n retrieves the current production status of Factory 1 using the authentication service of the S3I Identity Provider, the directory service provided by S3I Directory and an AMQP message exchange provided by S3I Broker

```
{
    "identifier": "s3i:4711",
    "name": "Factory 1",
    "description": "Directory entry for the I4.0 System Factory 1",
    "accessRules": [
        {
            "permissionPerObject": [
                {
                    "s3i:4712": [ "READ"]
                }
            ]
        }
    ],
    "endpoints": [
        "s3ib://s3i:4711",
        "tcp://factory_1"
    ],
    "hasThings": [
        "s3i:4711-cnc",
        "s3i:4711-kuka-roboter",
        "s3i:4711-fanuc-roboter"
    ]
}
```


Fig. 5 JSON-based meta information of Factory 1 that is based on the Semantic Data Model and centrally stored in the S3I Directory

understand each other by means of the predefined semantics. More importantly, the S3I ensures the security of data communication and resources based on CIA principles since OAuth 2.0 and role-based authorization policy are used in the central services.

5 Conclusion

Faced with the heterogeneous nature of production systems, their spatial distribution in different locations, and the trends associated with large amounts of data, a centralized infrastructure is needed to connect everything decentrally. We propose in this paper the concept of integrating an IoT communication infrastructure in production systems using the domain-independent S3I, which was developed originally for Forestry 4.0 Things. The provided simulation-based example demonstrates the application with a comprehensive method, ensuring interoperability in a heterogeneous production network while taking the security CIA aspects into account. Besides, the S3I does not limit the resource of I4.0 Things to be centrally hosted in the service provided by the infrastructure, but rather decentralized. Therefore, from this perspective, S3I can be scaled to any size as long as the server allows. The demonstrated application also illustrates that S3I is generally applicable as an IoT solution, regardless of the domain. Consequently, the use of S3I could be understood as a promising solution for an enlarged and secured IoT. Future work will focus on specific and classic security issues, such as DoS, injection, and man-in-the-middle, and analyze the vulnerability and reliability of S3I under these attacks. Additionally, lightweight data communication needs to be considered at the level of communication protocols and semantics as well.

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