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Affordable Data Integration Approach for Production Enterprises

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Abstract

The manufacturing industries in a number of high-labour-cost economies are undergoing a shift towards increased automation and intelligence typified by the 'Industry 4.0' paradigm. Advances from computer science research including digital informatics enables the addition of intelligence and autonomy to the flexible and reconfigurable manufacturing systems developed by manufacturing systems research. One such advance is the development of Data Distribution Services (DDSs) that enable the robust and timely distribution of high-quality data in a scalable manner. This paper describes how a DDS can be used to integrate systems across a production enterprise, including directly on a shop floor rather than using additional specialised shop floor integration components often required by other communications protocols.

Keywords: Digital Manufacturing System; System Architecture; Integration

1. Introduction and Motivation

Strategic industrial sectors in the UK and other developed economies face a diverse and evolving range of challenges. The aerospace and automotive sectors are facing rising demand for highly customised complex products in smaller and more variable production volumes while remaining cost-effective. The food and healthcare sectors likewise face customer-driven requirements for increasingly personalised products, produced in response to dynamic demand, with transparency in the origins and creation of the products. All sectors are furthermore seeking increased responsiveness, productivity, and competitiveness in the global market.

In response to this, the market as a whole has acknowledged the importance of 'Industry 4.0'-type digital manufacturing approaches that incorporate data-driven cyber-physical production systems [1]. These technologies are expected to "account for more than 50% of planned capital investments", and is projected to be "in the range of €140B annual investment across Europe alone" [2]. This new digital manufacturing paradigm presents a number of challenges and opportunities for the sector, both in terms of commercial production businesses, and the supporting research and development.

The primary underlying developments are those that leverage new informatics and data analytics techniques. For example, the use of embedded smart devices allows organisations to distribute their data processing and capture more fine-grained information on which to make and automate their decisions [3–5]. This 'internet of things' approach can be taken beyond the factory to cover more of the product lifecycle through the use of digital object footprint tracking [6,7]: in-use data can be fed back into the design or production stages of the system in order to drive improvements, and decision-making can happen 'at the edge', improving responsiveness to disruption. On the factory shop floor these opportunities manifest not only in increased levels of automation, but also through increased integration. This integration is both between shop floor equipment and between the shop floor and the higher-level systems such as planning and scheduling. The data these integration channels are required to carry is often highly complex, for example advanced metrology data required for metrology-assisted approaches [8–11]. This complexity and need for near-real-time decision-making is also driving the

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application of machine learning, cognitive computing, and autonomic approaches to production systems [12–15].

In order to accomplish this digital transformation and enhancement, a number of challenges must be addressed. Not only must diverse processes and disruptive technologies within the same production system platform be integrated, these processes and technologies also have sector-specific requirements and regulations for the accuracy, dexterity, and reliability of automation which must be accommodated.

Although such autonomy is finding increasing uptake in industry, the transition will occur over time rather than all at once. This leads to a requirement to maintain interoperability, standardisation, and integration with legacy systems. At all stages of this integration there is usually a requirement to maintain a human-in-the-loop, which raises a variety of additional sociotechnical challenges around human-centric communications and collaborative decision-making.

Traditional production conventions are being challenged in turn by these developments, and new systems architectures are required to address this. The UK industrial strategy [16–18] seeks to position the UK as a world leader in Industry 4.0 research and uptake. There are two key factors to achieve this global leadership role:

Supporting businesses in the development of cyber-physical industrial technology products. The Made Smarter Review identified [19] a number of business-oriented recommendations intended to achieve this world leading position for the UK. They can be summarised as targeting an increase in leadership through strategic vision, adoption of "industrial digitalisation technologies" (roughly synonymous with cyber-physical systems), and supporting innovation through new innovative companies. Any solution must therefore be affordable, practical to implement, and aligned with industrial strategy.

Creating new value streams based on data analytics and AI applications. In their review of opportunities and challenges of Industry 4.0, PricewaterhouseCoopers identified ten key findings [2]. Although some highlight how much of an impact Industry 4.0 is likely to have, all of them acknowledge the value of data and some go further in highlighting the requirement to share data across the enterprise and act on it with analytics and other disruptive software applications.

We therefore present the following as contributions:

- An integration approach for cyber-physical systems that:
  - supports businesses through affordability in terms of reduced cost and technical effort,
  - enables the development of production systems that are both data-driven and data-rich, and
  - connects the entire production enterprise through a fully integrated data platform.
- A summarised state of the art review of production integration, and justification for a single technology (Data Distribution Service, DDS) to be the basis of this approach, rather than a mix of other technologies.
- A concrete example for how this integration approach can link data from goods-in, via shop floor automation, to goods-out.

2. Traditional Approach and State of the Art Integration

In order to meet the sector drivers discussed in Section 1, production systems are becoming more and more flexible. Enabling this flexibility requires the simple, widespread, and timely communication of data at the shop floor and adjacent levels (in terms of the traditional automation hierarchy).

Production enterprises taking a digital manufacturing approach beyond this functional flexibility require high-quality knowledge on which to base their decisions. This knowledge requires the dissemination of data throughout the entire enterprise, avoiding the silos and breaks in data flows that are common in traditional enterprise architectures.

These traditional enterprise architectures typically divide the informatics devices into two main levels: the Operational Technology (OT) on the shop floor, and the Information Technology (IT) elsewhere [20,21]. This dichotomy naturally arose as equipment similar to that used in traditional IT began to gain traction closer to the shop floor equipment (for example the introduction of computer numeric control, programmable logic controllers, computer aided design and manufacturing, and manufacturing execution systems). However, the techniques, staff, and organisational structures used to support and maintain them remained separate, leading to different integration paradigms and approaches at the OT and IT levels.

Given the potential improvements to productivity in industrial production systems offered by digitalisation, a number of integration approaches for integrating shop floor equipment have been developed. These cover the entire spectrum of developments, including commercial products, academic techniques, standards-based frameworks, and proprietary vendor-specific approaches [22–31].

Although a full review would be beyond the scope of this article, many approaches exist for integrating shop floor equipment at the OT level [24,29,30]. One example from the discrete manufacturing domain (in this case the aerospace sector) is Open Platform Communications - Unified Architecture (OPC-UA, [24]), a widely supported and fully-featured integration standard that is the *de facto* standard approach for Industrie 4.0 activities [32], and therefore also for many digital manufacturing activities in other countries.

OPC-UA is an industrial communication protocol for machine-to-machine data transfer. As it was developed by a consortium of leading industrial automation suppliers it has a large base of drivers and support for shop floor equipment from a wide range of vendors. Although it initially had quite a well-defined scope, it has been extended to support mechanisms such as publish-subscribe and RESTful (i.e. HTTP-based and deterministic) communication [33,34].

Even more approaches exist for integration of IT software systems [35], and therefore a full review is also beyond the scope of this article. Of note in this context however is the Data Distribution Service (DDS, [28]) standard for machine to machine networking. DDS is a middleware for platform-

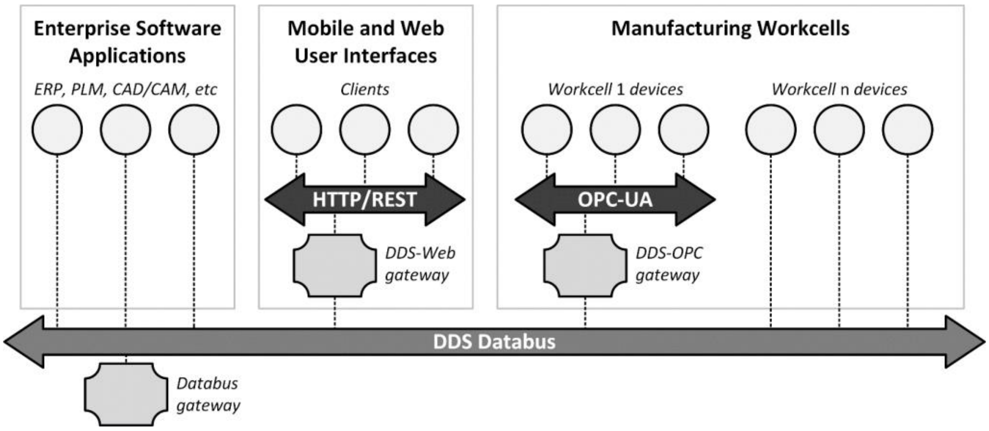

Figure 1. Conventional multi-platform approach to manufacturing enterprise IIoT integration.

independent data-centric systems. Originally designed for distributed software development, it has found applications as diverse as flight control and traffic control systems, programmable logic controllers, underwater robotics, and extra-terrestrial rovers [36]. In line with its original purpose, DDS utilises the publish/subscribe pattern to decouple producers and consumers of data and thereby make large distributed systems significantly less complex to maintain. Unlike other publish/subscribe communication standards such as Message Queuing Telemetry Transport (MQTT, [37]), DDS is brokerless and so has no central point of failure.

Both OPC-UA and DDS are identified as core connectivity standards for the Industrial Internet of Things (IIoT) by the Industrial Internet Consortium (IIC) in the USA [21]. Given their different scopes and foci, the IIC suggests that different scenarios call for different approaches, and that the connectivity standards should be seen as complementary rather than competing. In current integration practice, the usual approach is to take separate integration approaches for the OT and IT levels of the enterprise and then provide a bridge between the two. OPC-UA is proposed as the solution for OT integration due to its wide library of drivers, and DDS is proposed as the solution for IT integration due to its flexibility, data-centricity, and built-in parallelism [21,38,39]. Any externally-facing or mobile interfaces are provided through an additional webserver gateway (using HTTP/REST protocols).

This multi-platform approach is shown in Figure 1, based on a diagram from the IIC in their Connectivity Framework documentation [21].

3. Proposed Approach

In contrast to the approach described above and in the literature [40,41], we propose an alternative whereby the IT and OT levels both use a single platform for their integration, simplifying adoption and reducing the costs of implementation.

Out of the two currently used technologies, DDS was chosen over OPC-UA for the single integration platform. Although it might be possible to link OT and IT with OPC-UA, the lack of standard application programming interfaces (APIs) in general purpose programming languages would make this prohibitively complex. Particular difficulty would most likely be encountered when communicating between higher-level enterprise systems or with non-manufacturing IT systems such as data analytics or learning software.

The primary advantage of this merged approach over the separated approach is a reduction in architectural complexity. The usual separated approach requires two or three platforms to be used across the enterprise architecture: one for OT integration, one for IT integration, and potentially another to bridge the two. In contrast the proposed merged approach only requires one platform. This results in a number of additional implementation benefits beyond the functional ones:

- Reduced technical effort to design an effective approach.
- Reduced integration effort to deploy the approach.
- Increased standardisation across the enterprise.
- Simplified maintenance.
- Reduced technical knowledge requirement for use.
- Reduced cost to purchase and implement software, and reduced cost of training and maintenance.

Reduction in cost is therefore also in terms of reduced technical integration effort involved and in terms of increased utilisation and reduced friction through increased standardisation. The use of a single platform simplifies ongoing maintenance and updates, and requires less training to implement and maintain the platform.

This increased affordability is not just a driver for small enterprises. Existing integration effort in Original Equipment Manufacturers (OEMs) and Tier 1 companies generally falls to traditional integration partners. There is an increasing desire to bring integration knowledge in-house [42,43]. This may drive a move from “device integration by few process engineers” to “software integration by many software engineers” [38]. Such a move would harmonise with the approach proposed here.

4. DDS-based Production Enterprise Integration

DDS has found some application in an academic context to demonstrate equipment-level integration and is widely used for systems integration outside of the manufacturing industry, for example in power, military, and space systems [36] where the resilience and scalability of the system are paramount.

Despite this, it is not widely used in the manufacturing industry, either for shop floor or enterprise systems. However, with manufacturing systems becoming increasingly complex,

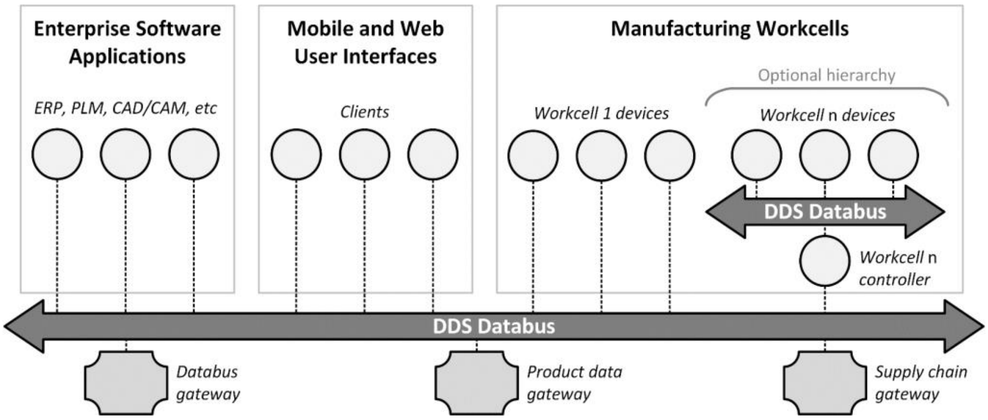

Figure 2. Proposed DDS-only approach to manufacturing enterprise IIoT integration, showing both "flat" and "hierarchical" integration.

with more and more devices being integrated via data busses, with large volumes of smart sensors being deployed, and with the integration extending beyond the shop floor and into the supply chain, there is a requirement for a scalable, simple, resilient manufacturing data integration method. With that in mind, we now present an overview of our proposed approach spanning both the shop floor and higher-level systems.

Figure 2 shows our approach in the style of the previously presented IIC diagram. The manufacturing resources can either be connected directly to the main DDS databus in a flat network structure, or multiple busses can be cascaded in a hierarchy with the workcell controllers acting as gateways between them. Direct connection has the advantage of a simple structure and maximum data visibility with minimum latency, but risks network congestion in high-data-volume scenarios. Cascading the databusses requires more integration effort to avoid data access issues or higher latency, but the self-similarity of the approaches means the additional effort is minimised. Alternatively, DDS allows users to set quality of service (QoS) parameters that will allow the middleware to prioritise time-sensitive data over less urgent information.

By design, DDS removes the network programming and connectivity considerations of typical manufacturing system integration, instead taking a 'software-defined network' approach. This means that, provided the manufacturing devices are connected to a common network, the routing of data is handled automatically via an integrated 'discovery' function. The addition or removal of devices is likewise handled automatically, simplifying the process of scaling up or down in response to changes in demand.

The web and mobile clients could either be connected through the existing HTTP/REST protocols, or directly connected to the DDS databus [44–46] in the same way as the "Software Applications" already present on the diagram. They have therefore been left implicit for clarity and to save space.

The use of a software integration framework rather than a device integration protocol enables the simple extension of the single platform to include both product lifecycle information and information from the wider supply chain. This 'digital product lifecycle' approach allows for greater and more efficient integration between supply chain entities, and provides production enterprises with more information on the use of their products. This information can be fed back into the production processes, informing the design, planning, scheduling, or manufacture/assembly functions.

5. Implementation Example

Although examples exist of DDS-based integration of workcells themselves [42], data integration across the production enterprise is less well studied. In this section we present an example, shown in Figure 3, of our approach linking different enterprise functions with the shop floor operations.

Within the databus, multiple *Topics* are defined. These define the types of data published to this topic, and each has a defined data model. Topics are entirely software, and can be added or removed as required. Devices can subscribe to topics, and can further filter based on keys, such as the *PartID*.

When a part is received at goods-in, it is tagged with a unique identifier, for example an RFID tag which can be attached directly to the part or to the pallet on which the part is transported throughout the process. This creates a unique *PartID* key so that future data samples in the databus can be linked back to the correct part. This unique *PartID* and the flat, accessible nature of the databus means information about this part is accessible to all other devices on the same bus.

After registering a part in the system, a quality of supply process can be carried out. The nominal part design can be retrieved from the Enterprise Resource Planning system (ERP) and offsets for key surfaces or features noted in *MetrologyData* samples also keyed to the *PartID*, for example correct fastener *GripLength* values.

Once the incoming quality of supply information has generated the required fasteners for the part, these can be retrieved in a stock room through a mobile device and added to the *PartID*-linked kit. Automatic stock monitoring can be used to trigger re-orders for consumables that run low.

Once the part enters the automation workcell, the most up to date production process is retrieved by the control system and parameters are automatically adjusted by the offsets that were previously identified and published on *MetrologyData*.

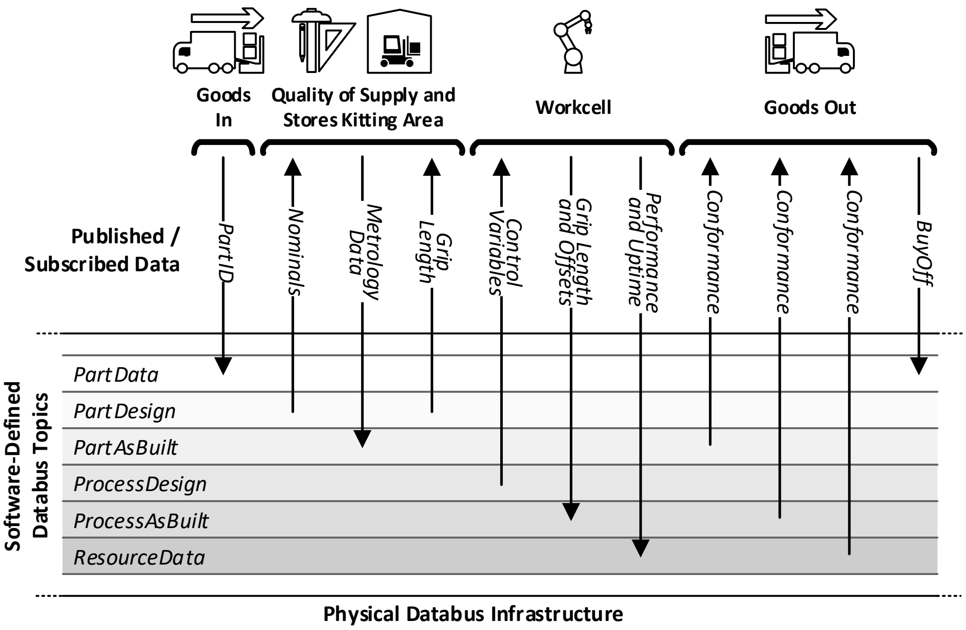

Figure 3. Production example of through-enterprise databus

The build instructions for the operator in the cell are updated with the fastener *GripLength* values and displayed on an HMI. This ensures that the assembly process is as efficient as possible, removes the potential for errors due to out of date instructions, and reduces the amount of rework required by accommodating part variation in a flexible process.

All process performance data is collected from the automation controllers and operator, used to inform the part status for later processes, and builds up the qualification data over time for final buy-off by the customer.

All the data is published to specific topics and keyed to the PartID. DDS is an asynchronous communication standard – any published data can be retrieved after it was sent unless it was updated with a new value. In this way, devices are decoupled from the origins and destinations of data, but also from the time in which the data was generated, making DDS an extremely robust solution.

6. Summary and Conclusions

Manufacturing organisations of all sizes are faced with increasing requirements for integration of their systems, particularly in terms of data acquisition and sharing. In response to this, they are seeking lower-cost approaches to integration without relying on traditional integrators supplying "black box" solutions they do not understand. We present a simple and affordable architectural approach to data integration that addresses these requirements through the use of DDS databus technology. This approach reduces architectural complexity, integration effort, and cost, while simultaneously increasing system scalability, resilience, and interoperability.

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