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An event-driven manufacturing information system architecture for Industry 4.0

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Future manufacturing systems need to be more flexible, to embrace tougher and constantly changing market demands. They need to make better use of plant data, ideally utilising all data from the entire plant. Low-level data should be refined to real-time information for decision-making, to facilitate competitiveness through informed and timely decisions. The *Line Information System Architecture* (LISA), is presented in this paper. It is an event-driven architecture featuring loose coupling, a prototype-oriented information model and formalised transformation services. LISA is designed to enable flexible factory integration and data utilisation. The focus of LISA is on integration of devices and services on all levels, simplifying hardware changes and integration of new smart services as well as supporting continuous improvements on information visualisation and control. The architecture has been evaluated on both real industrial data and industrial demonstrators and it is also being installed at a large automotive company. This article is an extended and revised version of the paper presented at the 2015 IFAC Symposium on Information Control in Manufacturing (INCOM 2015). The paper has been restructured in regards to the order and title of the chapters, and additional information about the integration between devices and services aspects have been added. The introduction and the general structure of the paper now better highlight the contributions of the paper and the uniqueness of the framework.

Keywords: automation; agile manufacturing; manufacturing information systems; service-oriented manufacturing systems; event-driven architecture

1. Introduction

Future industrial manufacturing systems need to make better use of the data (Hill and Smith 2009; Panetto and Molina 2008). Low-level data have to be transformed into useful information and smart services need to be integrated to support decision-making. In addition, future manufacturing systems need to be productive, flexible, competitive, sustainable, secure and safe. They have to be designed to reduce waste of material, capital, energy and media. Improved control, reconfigurability, optimisation and human interaction in manufacturing processes are also important for future manufacturing (Blanc, Demogodin, and Castagna 2008; Bi and Lang 2008).

The challenge to manage data, transform it into knowledge and make smart automated decisions, has drawn a lot of attention during recent years. The main focus has been on the overall architecture, for example, in collaborations like Industry 4.0 (Industrie 4.0 Working Group 2013), Smart Manufacturing Leadership Coalition (Smart Manufacturing Leadership Coalition 2016), Internet of Things (Atzori, Iera, and Morabito 2010), the Industrial Internet (Evans and Annunziata 2012), and cloud robotics and automation (Kehoe et al. 2015).

Industries and device manufacturers are, however, reluctant to implement these new technologies due to unclear possible benefits, lack of clear implementation details, and the seemingly large investments required (Dawson 2014).

An important driving force for adaptation may therefore be the possibility to integrate a large variety of devices and new services into existing systems. Most automotive companies already use advanced information systems (Dai et al. 2012). However, many of them lack important aspects to simplify integration.

Plants often use a wide range of devices, based on different technologies from different eras. Some devices originate from when the plant was built and devices have then been added as part of continuous improvements. Retrofitting legacy devices is thus a particularly important aspect. It must be possible to integrate them regardless of their capabilities or technology.

This paper presents the *Line Information System Architecture* (LISA), an innovative, yet simple architecture and design pattern for rapid integration of smart services into existing factory infrastructure. LISA is an event- and

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service-based information system architecture that is used to integrate devices and services, also called the Tweeting Factory (Lennartson et al. 2015). Simple messages (tweets) from all kinds of devices are sent out and transformed into high-level knowledge that is used by smart services for online monitoring, control, optimisation, and reconfiguration (Theorin et al. 2015).

Parts of the LISA architecture have been incorporated at one of our partners, an industrial automotive industry, where thousands of devices like Programmable Logic Controllers (PLCs), robots and scanners have been integrated during the last five years at multiple plants. A large variety of services, from SMS messages for Andon signals (process notifications) to the main MES system, have been connected. The architecture has also been evaluated using historical data from another automotive industry partner. LISA is able to handle layout and structural changes on the plant floor and allows a large diversity of devices and applications. Furthermore, LISA simplifies changes and updates when calculating Key Performance Indicators (KPIs), not only for new, but also for historical data. The importance of using KPIs for manufacturing companies is pointed out in Cao et al. (2015). Innovative services, like energy optimisation of robot motions, CNC-data aggregation and Grafchart control have also been implemented to prove the simplicity to integrate new services.

In Section 2, the concepts of some common architectures are introduced. In Section 3, LISA is described, and in Section 4, selected services are explained. Finally, industrial use of LISA is described in Section 5, and conclusions are presented in Section 6.

2. Architectures

Information and communication architectures have been proposed in various areas in manufacturing research, for example, in planning (Umble, Haft, and Michael 2003), holonic manufacturing (Van Brussel et al. 1998), control (Dai et al. 2012; Babiceanu, Chen, and Sturges 2004; McFarlane et al. 2003), service-oriented and cloud-based architectures (Shena et al. 2007; Morariu, Borangiu, and Raileanu 2015) and agent systems (Leitao, Marik, and Vrba 2013).

These architectures require information about the real-time performance and behaviour of the manufacturing plant. However, few are focusing on how to connect the large variety of devices and how to handle changes over time. Many companies have developed their own solutions, sometimes based on international standards such as ISA95 (ISA 2013). The solutions are typically based on Point-to-Point (PtP) integration.

2.1 PtP integration

When new functionality and systems are added, they need to be rapidly integrated with existing systems. The traditional integration approach in manufacturing is to connect applications on a PtP basis using the client/server pattern. The pattern requires that the server and the client know about each other. The number of connections in a fully connected network increases quadratically with the number of applications. This is known as ‘spaghetti integration’ and makes the system rigid and hard to maintain (Boyd et al. 2008). Each time an application is added, all other applications need to be updated to be able to interact with the new application.

It is common that applications can only communicate through proprietary or specific protocols, and applications may require external message translators to communicate with each other. This is, for example, the normal case for communication between PLCs from different vendors. Another challenge is communication between the different levels of ISA95, see Figure 1, known as vertical integration.

A common solution in industry is to use OPC to standardise how to access devices over a network. The main problem with only using OPC is that it tends to become a PtP solution, where, for example, the PLC variable structure must be known in many places. To handle this, many companies include a lot of logic in the devices to aggregate and transform data that is accessed over OPC.

The PtP approach poorly supports business requirements (Ribeiro, Barata, and Mendes 2008). Yet, industry has been slow to migrate to new approaches, mainly due to the cost of replacing their established legacy systems based on PtP (Boyd et al. 2008). However, migration has been significantly accelerated by the advent of Service-Oriented Architectures (SOAs) (He and Da Li 2014).

2.2 Service-Oriented Architecture

SOA is a distributed software architecture where self-contained applications expose themselves as services, which other applications can connect to and use. To reach its full potential, SOA applications should be self-describing, discoverable, and platform- and language-independent. This leads to loose coupling and high flexibility.

SOA has recently received much attention in both academia and industry. The adoption of SOA in a company typically starts as an IT initiative to improve infrastructure efficiency and can then mature into optimised use for business purposes

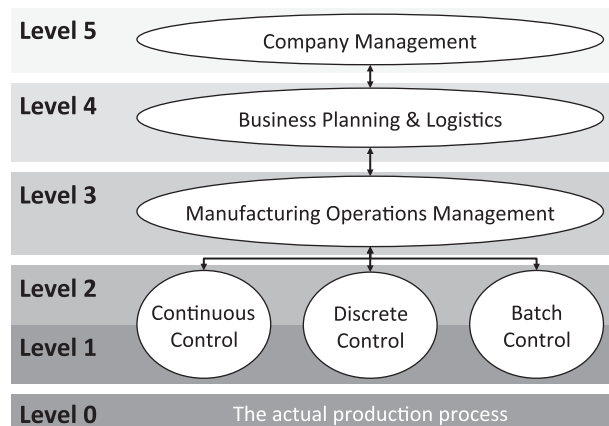


Figure 1. Functional hierarchy as defined by ISA95.

(Welke, Hirschheim, and Schwarz 2011). SOA is widely used on the business level and is expected to revolutionise manufacturing in a similar fashion (Li and Madnick 2015; Mueller et al. 2010).

The further down the hierarchy in Figure 1, the shorter the task time frame. On level 1 it is common with hard real-time requirements, with deadlines in the order of milliseconds. The devices which execute on level 1 often have strictly limited memory and computational power. There is a trade-off between flexibility and real-time performance (Theiss, Vasyutynskyy, and Kabitzsch 2009) and thus, the further down SOA is wanted, the more performant (and hence less flexible) it needs to be. Most SOA tools are tailored for business processes, which do not have strict timing or resource requirements. Thus, these tools cannot be used for manufacturing processes. However, there have been initiatives to bring SOA to levels 1 and 2 by customising the web service technology for resource constrained devices (Cucinotta et al. 2009; Dai et al. 2014).

2.3 Event-Driven Architecture

Even though SOA conceptually offers loose coupling and is intended to be distributed, service orchestration is typically done centrally, with the orchestrator taking control of the involved services. SOA 2.0, also known as advanced SOA or event-driven SOA, is the next generation of SOA that focuses on events, inspired by Event-Driven Architecture (EDA). SOA 2.0 enables service choreography, where each service reacts to published events on its own, rather than being requested to do so by a central orchestrator.

EDA is extremely loosely coupled and highly distributed by design. An event creator only needs to know that the event occurred, it does not need to know anything about who is interested in the event or how it will be processed (Michelson 2006). Event data should be immutable since it is then always (thread-)safe to send the events within and between applications. With EDA, applications turn from synchronised and blocking to asynchronous and non-blocking (Roland and Allen 2016).

3. Line Information System Architecture

LISA is an EDA that provides loose coupling of applications and devices, as well as a flexible message structure for integration. The core components of LISA are the message bus, the LISA message format and communication and service endpoints. They enable creation and transformation of events into usable information in a loosely coupled way, and will be described in the following sections.

3.1 LISA events

A common approach for information systems is an object-oriented structure for event types and events (Cheng et al. 1999). LISA on the other hand uses a prototype-based approach (Taivalsaari and Moore 2001). Prototypal inheritance, unlike object-oriented inheritance, is achieved by cloning and refining an object, here an event. This makes event creation, identification and filtering less rigid, as there is no strict class hierarchy enforcing class relations.

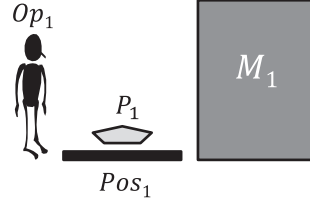


Figure 2. An example workstation.

Table 1. Attribute patterns used for creating and matching the example events.

| | | | |
|------------------|--|----------------|---|
| O_1^\downarrow | name: O_1^\downarrow location: $[Line_1, WS_1]$ resources: $[Op_1, Pos_1]$ rfid: $_$ | O_3^\uparrow | name: O_3^\uparrow location: $[Line_1, WS_1]$ resources: $[M_1, Pos_1]$ rfid: $_$ |
| O_2^\uparrow | name: O_2^\uparrow location: $[Line_1, WS_1]$ resources: $[M_1, Pos_1]$ | M_1^s | name: M_1^s location: $[Line_1, WS_1]$ status: {mode: $_$, currentTool: $_$ } consumption: {energy: $_$, duration: $_$ } |
| O_2^\downarrow | name: O_2^\downarrow location: $[Line_1, WS_1]$ resources: $[M_1, Pos_1]$ consumption: {energy: $_$, duration: $_$ } | | |

When something happens, for example, when a machine changes state, an event with information about the change is sent. A LISA event is defined as $e = \langle id, t, AV \rangle$, where id is a unique event identifier, t is a timestamp, and $AV = \{attr_1: value_1, \dots, attr_k: value_k\}$ is a set of ordered attribute–value pairs describing the event.

Definition 1 (Attribute pattern). An attribute pattern $ap = \langle AV_{ap}, A_{ap} \rangle$ is a tuple including a set of ordered attribute–value pairs AV_{ap} and a set of attributes A_{ap} . If $e_1 = \langle id_1, t_1, AV_1 \rangle$ such that $AV_{ap} \subseteq AV_1$ and $A_{ap} \subseteq A_1$, where A_1 denotes all the attributes found in AV_1 , then e_1 is matched by ap . This is denoted $e_1 \leftarrow ap$.

An attribute pattern is used to match, identify, filter and create events. In this article, a pattern is denoted, for example, $ap = \{attr_1: value_1, attr_2: value_2, attr_3: _ \}$, where $AV_{ap} = \{attr_1: value_1, attr_2: value_2\}$ and $A_{ap} = \{attr_3\}$. When the value is replaced with ‘ $_$ ’, that attribute can have any value. Values can also be a list of ordered attribute–value pairs or a list of values. Hence, hierarchical data structures can be represented.

Patterns can be defined freely by the user and are not enforced by LISA. However, the events receivers will match events based on patterns, which makes the definitions important. These patterns cannot be standardised for the lower levels of ISA95 since each plant has a unique system structure with a large diversity of devices.

Example

Consider the workstation WS_1 in Figure 2. It consists of an operator Op_1 , a product instance P_1 with product identifier p_1 , a position Pos_1 and a machine M_1 . The workstation can perform three operations: O_1 – place a product at Pos_1 , O_2 – use M_1 to process the product at Pos_1 , and O_3 – move the product at Pos_1 to the next workstation. Each operation is executed once per product instance and can be traced by start and stop events. Often, there are events which are not observable. Here, only $O_{1p_i}^\downarrow$, $O_{2p_i}^\uparrow$, $O_{2p_i}^\downarrow$, and $O_{3p_i}^\uparrow$ are observable, where $O_{kp_i}^\uparrow$ and $O_{kp_i}^\downarrow$ denote the start and stop events, respectively. These events are fired once per product instance P_i .

Events do not have to be related to the execution of an operation, for example, resource alarms, running mode changes or the start of a lunch break. Here, the machine fires an M_{1i}^s event whenever the machine has changed execution mode (operating, idle, or down) and the events are based on the attribute patterns shown in Table 1.

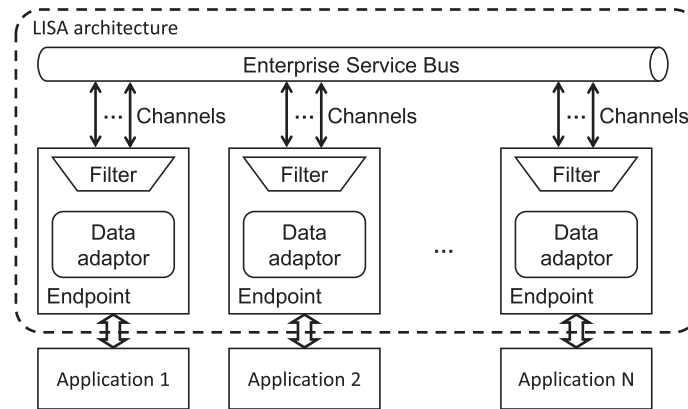


Figure 3. Overview of the LISA communication architecture.

3.2 Message bus

It is important with a standardised, structured and generic concept to describe and implement loosely coupled software applications that are heterogeneous, disparate and deployed and run independently. Hence, LISA uses an Enterprise Service Bus (ESB), a component that takes care of message routing between distributed applications. To avoid PtP connections and ensure loose coupling, the ESB should support the following Enterprise Integration Patterns (Hohpe and Woolf 2003):

- *Message*: The information or data are packaged into a message that can be transmitted on a message bus.
- *Messaging*: Messages are transferred immediately, frequently, reliably and asynchronously using customisable formats. Messaging is event based: when there is a new message, it is sent to the message bus.
- *Publish-subscribe channel*: When a message is sent on a publish–subscribe channel, a copy of the message is delivered to each channel subscriber.
- *Message filter*: If the content of an incoming message does not match the criteria specified by the message filter, the message is discarded. This pattern allows each application to further filter incoming messages.

In the LISA prototype Apache ActiveMQ is used, but it could be replaced by any ESB supporting these patterns.

Figure 3 shows an overview of the communication architecture of LISA. The connection of applications (devices, services, external applications) to the ESB is through endpoints, which are responsible for (1) adapting the events and information according to the LISA message format, (2) publishing LISA messages on the corresponding channels on the ESB and (3) filtering incoming LISA messages from the ESB. If an application is modified (e.g. due to hardware replacement, variable renaming, or new measurements), only its endpoint needs to be changed. No other endpoints or applications need to be updated.

3.3 LISA message format

The LISA message format is designed to be simple and to enforce as little structure as possible. It consists of a header and a body. The header contains information related to message sending and routing. The body is an ordered key–value map between attributes (the keys) and their values. Values are usually of primitive data types, but can also be lists or maps. Hence, arbitrary hierarchical structures can be built and sent in LISA messages. Two attributes are mandatory in the body, namely an event *id* and an event *timestamp*, otherwise there are no constraints.

In the LISA prototype JSON is used as data format, but it could be replaced by any data format where maps and lists can be expressed.

Each plant has a unique system structure with different types of devices and LISA should be able integrate any device on levels 1 and 2. LISA makes this possible by letting the users define the events. This might be considered a drawback, but it means that it is easier to change or extend events, which indeed makes LISA flexible.

LISA messages sent on the ESB are immutable. To refine a LISA message, a new LISA message is created and sent to the ESB. The new message will have the same *id* and *timestamp*, but the content of the message may otherwise change arbitrarily.

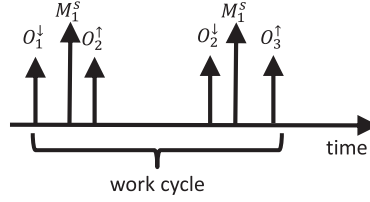


Figure 4. Events fired during one work cycle. Note that the first and second M_1^s are different events with the same name. They have different id , t and data.

3.4 Communication endpoints

The connection between applications (communication devices, services, external applications) over the ESB is done through communication endpoints. Many devices have limited capabilities and knowledge and they communicate with different device specific protocols and interfaces. To replace all production equipment with new devices which all support the same specific protocol and interface is infeasible. Instead, the diversity of devices has been embraced and in LISA, devices are integrated with communication endpoints.

A communication endpoint is an adapter between the ESB and a device. Device event data are converted to the LISA message format and are published on ESB channels. Similarly, a communication endpoint filters events and converts and communicates event data to the device. With a communication endpoint, practically any device can be integrated into LISA. If an application is modified (for example, due to hardware replacement, variable renaming or new sensors), only the corresponding communication endpoint needs to be updated. Devices could also send data directly on the ESB if they support that.

The messages from devices are usually low level, for example, a few bytes where each bit represents some variable. These bytes should be converted to structured data by transformation services. A key pattern in LISA is to perform data transformation logic outside the devices itself. If new data are needed, considerably more work is required to update all PLCs and robots in a plant than to deploy an updated service.

Example continued

There are three communication endpoints in the workstation: one connected to an RFID reader, one to M_1 , and one to a PLC. The events fired during one work cycle are shown in Figure 4. Event O_1^\downarrow is fired by the RFID reader when it senses that a product is placed at Pos_1 . The first M_1^s event is fired by M_1 when changing from idle to operating mode. Then, the PLC fires the start of the processing operation, O_2^\uparrow . When the processing is completed, the PLC fires O_2^\downarrow and M_1 fires another event, M_1^s , telling that it is in idle mode. The work cycle is completed with O_3^\uparrow , which fires when the RFID reader senses that the product is removed.

3.5 Service endpoints

When calculating KPIs and controlling a plant with an MES system, most industries have similar structures. Hence, the low-level events should be transformed and updated to a more standardised structure with attribute names and semantics based on international standards like ISO 22400 (ISO 2014). This is managed by the service endpoints.

One challenge is to manage all the different devices. Many devices know little about the manufacturing. In the workstation example, only the RFID reader knows which product is at the workstation, or rather which product identifier. To calculate various KPIs, it is therefore necessary to transform, update and aggregate events.

LISA classifies three basic types of transformations: Fill, Map and Fold. Fill and Map add additional data to events and Fold transforms event sequences into new events.

Definition 2 (Fill). A Fill transformation transforms an event $e = \langle id, t, AV \rangle$ by appending a set of attribute–value pairs, that is, $\langle id, t, AV' \rangle = \text{Fill}(e)$, where $AV \subset AV'$.

Fill transformations only use static data. If applied to the same event, the result is always the same. A common use case is to add product identity and type based on an RFID tag, or to add information about the original event sender.

Often, an event needs information which depends on the current system state. If we study a system as a DES, a state can be identified based on an initial state and a sequence of events (Cassandras and Lafortune 2008). This is also true in the

LISA architecture. Let Σ^* be the set of all finite sequences of events over the set of all LISA events Σ . Then, given a finite sequence $s \in \Sigma^*$ ordered by the timestamp, the state $q \in Q$ of the system is defined by $q = \delta(q^0, s)$, where q^0 is the initial state of the system and δ is the transition function of the system, defined as $\delta : Q \times \Sigma^* \rightarrow Q : (q^0, s) \mapsto \delta(q^0, s)$.

The state of a specific part of the system R , such as a product or a resource, can also be identified by an event sequence. If we define R using an attribute pattern ap^R , then the current state of R is $q_R = \delta(q_R^0, s_R)$, where only events that match ap^R are included in the sequence s_R . The Map transformation permits to refine an event according to the current system state.

Definition 3 (Map). A Map transformation transforms an event $e = \langle id, t, AV \rangle$ by appending a set of new attribute–value pairs based on the current state q , that is, $\langle id, t, AV' \rangle = Map(e, q)$, where $AV \subset AV'$.

Fill and Map can be used to transform events in multiple steps, to simplify the implementation and to increase the flexibility. However, they do not change the unique identifier id or the timestamp t of the event. The transformation history and the event version could be stored as attributes to make it easier to trace the transformation chain.

Definition 4 (Fold). A Fold transformation is a function that transforms a finite sequence of events, $s \in \Sigma^*$, into a single new event, e , that is, $e = Fold(s)$.

Fold can be used to bundle a set of events. It can also implement advanced event pattern identification languages like Complex Event Processing (CEP) (Luckham 2002) or real-time languages (Perez et al. 2014). CEP formalises how patterns and knowledge are identified from a flow of low-level events, which results in high-level events (Cugola and Margara 2012).

Example continued

A Fill transformation updates RFID reader events with product identifier and product type attributes, that is, $O'_{1p_i} = ProductFill(O_{1p_i})$. A database that stores RFID tag numbers and their corresponding product identifiers and product types is used.

A Map transformation adds information about which product instance is at the workstation. This is known by listening to O'_{1p_i} events.

One Fold transformation tracks when a product first enters the system and when it leaves, resulting in an event with the lead time of each product instance. Another Fold transformation tracks all operation events and combines start and stop events into an operation event which can, for example, include durations and consumptions. There is also a Fold transformation that aggregates the machine events, for each hour and for each day, to an event about operating behaviour and energy consumption.

In summary, the following transformations are used:

- $e' = ProductFill(e)$. The product id and product type are added to events, where $e \leftarrow \{rfid, location\}$ and $e' \leftarrow \{rfid, location, productID, productType\}$.
- $e' = LastPositionFill(e)$. If a location is the last position for this product, it is added to the event. Here $e \leftarrow \{location, productID : p_{last}, productType\}$ and $e' \leftarrow \{lastPosition : true\}$. Observe that the transformation keeps all attributes, it is only the added key-value pair that is shown.
- $e' = ProductMap(e, q^L)$ is applied to events $e \leftarrow \{location, productID, productType\}$, that is, each location is mapped to the product located there (stored in the q^L states).
- $productMessage = ProductFold(\{e \in s | e \leftarrow \{productID : p_i\}\})$. Collects events related to a specific product identifier p_i and, after the last event, sends a product message. The message includes the time of the first and last events, the sequence of visited positions, and the aggregated operation energy consumption.
- $operationMessage = OperationFold(e_i \in \{O_i^\uparrow, O_i^\downarrow\})$. Collects operation events, O_i , and sends operation messages.
- $resourceMessage = ResourceFold(\{e \in s | e \leftarrow \{resource : rid\}\})$. Collects events that match a specific resource rid and sends a status message every hour and every 24 hr.

3.6 LISA flexibility

Example continued

The line is extended with two more identical workstations, WS_2 and WS_3 . O_3 now means moving the product in WS_1 to WS_2 and after the processing in M_2 , the product is moved to WS_3 (O_5). The complete line, $Line_1$, includes four transport operations (O_1, O_3, O_5, O_7), three processing operations (O_2, O_4, O_6) and three machines that send events.

When the new workstations are connected to LISA, the messages will include the new layout without changing the service endpoints. For example, $productMessage$ will include events from the added workstations, including information about

the longer lead time and the new processing steps. Also, *ResourceFold* will automatically detect the new machines and start to send resource messages for them. Since these messages follow a structure understood by the upper level information receivers, these upper services do not have to change either.

Absence of PtP communication as well as a multitude of event structures and event generators result in loose coupling between information levels. Using Fill, Map and Fold transformations provides increased flexibility. The example may seem trivial, but this flexibility does typically not exist for automotive manufacturers. Often, a PtP communication approach is used and the upper level systems require detailed understanding about current layout, making the system layout rigid.

3.7 Persistence

When an application failure occurs, for example, a random application crash, the application should be able to recover gracefully and should behave the same as if it had not failed. Ideally, other applications should not be able to tell if it had crashed or not. Of course, the timeliness will be affected, but the events generated by the crashed application should not be affected.

If all events are persisted, they can be replayed in the restarted application to make it reach the same state as when it crashed. The application can then proceed from there and produce the same events as if it had not crashed. Replay performance can be improved by occasionally persisting a state snapshot, which limits how much history has to be replayed. For practical reasons, there should be logic to avoid event duplicates during replay.

To store the whole history of events with the purpose to persist an application's state is called event sourcing (Roland and Allen 2016). Compared to persisting the state itself, there are some notable differences. With event sourcing, the exact same application behaviour can be replayed and analysed in detail. For example, if an application is found to be in an incorrect state it is possible to step through the replay of events to find out which event processing introduced the error. It might even be possible to go back and correct some such errors retroactively.

Another advantage of event sourcing is that it is possible to apply the event history to new applications. For example, if an application that calculates a new KPI is added, it might be possible to calculate that KPI retroactively for the whole history. Since LISA is based on event sourcing, with all events stored in a journal (Kuc and Rogozinski 2013), it is possible to change and add services and execute them on historical data.

4. Integration of services Into LISA

Due to its distributed nature, it is simple to integrate new services into LISA. New data can be identified in various devices and extracted via an endpoint. In many cases, this can be done without changing the low-level device code. In this section, KPI calculation services, energy optimisation services, CNC machining data services and control services are presented. These services have been evaluated either in a demonstrator at a university or in a real industrial situation.

4.1 KPI services

LISA does not enforce calculation of specific KPIs or require that the user follows a specific standard. However, to allow the user of LISA to, in a flexible way, define and calculate KPIs on current and historical data, it is important to use well-defined attributes and values.

Example continued

Product lead time, T_C , is the time between the initiation of operating a product and its final delivery. Here, T_C is calculated for a product P_i with the product identifier p_i using the time difference between the first and the last event. This is the time between placing the product P_i at Pos_1 and removing it from WS_3 .

The lead time is calculated in a *ProductFold* and is then added to the product message that the transformation sends out. The events have been transformed in a number of steps before the *ProductFold* creates the product message.

The event O_7^\downarrow is part of the following transformations:

- $O_{7prod}^\downarrow \leftarrow \{productID : p_i\} = ProductFill(O_7^\downarrow)$
- $O_{7last}^\downarrow \leftarrow \{lastPosition : true\} = ProductFill(O_{7prod}^\downarrow)$
- $Product_i \leftarrow \{leadTime, \dots\} = ProductFold(O_{7last}^\downarrow)$

Table 2. KPI attributes for the example events.

| O_2 | M_1 status | productMessage | ... |
|-------------|--------------------|--------------------|-----|
| startTime | operationTime | productID | ... |
| stopTime | downtime | Operations: [...] | |
| productID | idleTime | Consumption: [...] | |
| resources | Consumption: [...] | startTime | |
| consumption | Performance: [...] | stopTime | |
| ... | ... | ... | |

Downtime, T_D , is the time that a machine M_i is unavailable for operation and is defined as the sum of times between event pairs M_i^s that change mode to and from down. This is calculated in the *ResourceFold* transformation. With the same approach, idle time and operation time are calculated, and added to the resource messages.

The duration a particular product P_i stays at a certain position Pos_i is calculated as the time difference between P_i being put on Pos_i and removed from it. Aggregating time durations of all positions in the production line for a single product enables detailed visualisation and analysis of time intensive operations, see Figure 5(b).

These KPIs are calculated by services and added to the messages. Some examples are shown in Table 2. KPIs for product lead time, availability and product position times are quantified and visualised continuously for the LISA demonstrator, see Figure 5(a) and (b).

4.2 Energy optimisation services

The number of robots connected directly to a network is constantly increasing. They can send detailed information about their status, motion trajectories and operation timing. This enables new and innovative analysis and support.

Currently, a demonstrator is being developed that shows automatic visualisation of time and sequence diagrams of the robot work cycles, advanced monitoring of the welding process, error detection and troubleshooting support, and online energy optimisation and prediction services (Riazi et al. 2015; Lennartson et al. 2015). The algorithm for energy optimisation has been developed in the EU-project AREUS (Pellicciari et al. 2015). The algorithm can reduce the energy consumption of the robots by up to 30% (Vidarsson 2015). The input to the optimisation is created by retrieving and transforming events from the robots sent via LISA. The optimisation is based on the notion of hybrid operations. It is used as a common notion for activities in a factory, related to both products, manufacturing processes and automation solutions. The optimisation of a robot station using LISA is performed in the following steps:

- All devices send events during execution.
- The events are transformed and aggregated into hybrid operations.
- The hybrid operations are optimised.
- The new operations are sent to the robots and the PLC.
- As long as any of the robots' path is not manually changed, the station runs the optimised operations.

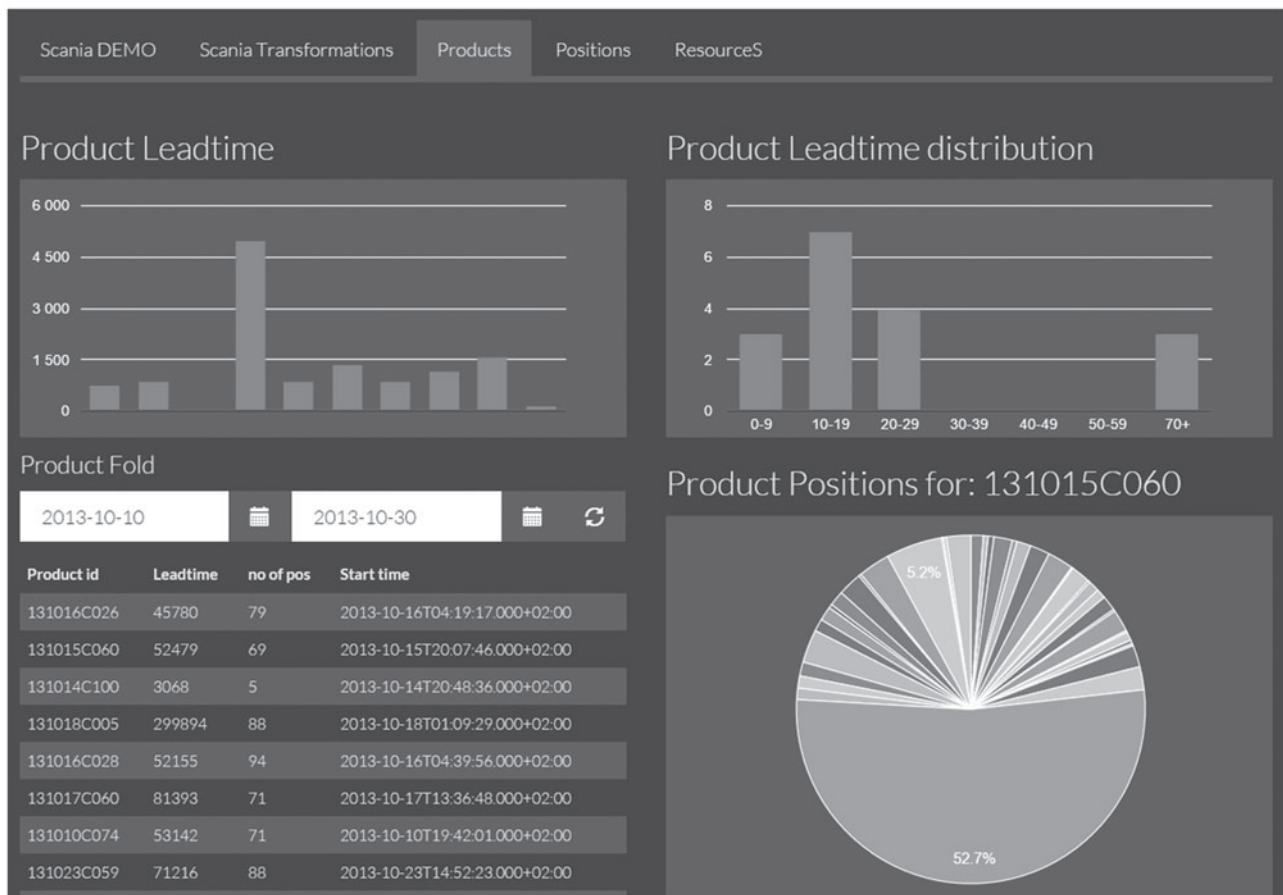
The framework for multi-robot scheduling and optimisation focusing on energy consumption is implemented in the tool Sequence Planner (Bengtsson and Lennartson 2014; Lennartson et al. 2010). Sequence Planner is an operation and task-planning tool that enables innovative modelling and algorithms for sequence planning and coordination. Sequence Planner gathers all the hybrid operations from the message bus, identifies their sequential relations and optimises the robot trajectories. The result is sent back to the robots via LISA. When minimising the energy of a robot station, Sequence Planner uses the nonlinear solver Ipopt (Wächter and Biegler 2006).

4.3 CNC machining services

Based on LISA as well as state-of-the-art technology, in for instance Industrie 4.0 (Industrie 4.0 Working Group 2013; Hermann, Pentek, and Otto 2015), and STEP-NC (ISO 2007; Lanab, Liua, and Zhanga 2008), the new Tweeting machine project develops Internet of Things functionality to provide rich information from CNC machining. The availability of such rich information will enable increased productivity and flexibility by improved or new functionality for design, process planning, tooling, operations and quality control that can be realised and directly implemented in industrial applications, see example in Figure 6.



(a) Online KPIs for machine availability.



(b) Online KPIs for product lead time (top) and time spent at each position for a single product (bottom).

Figure 5. KPI visualisation.

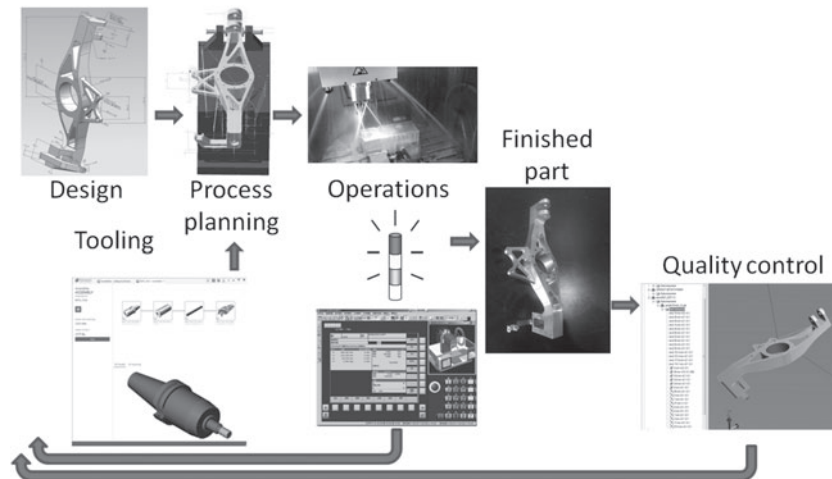


Figure 6. The new Tweeting machine.

4.4 Control services

Control using LISA has been implemented on a demonstrator system consisting of a real PLC connected to a physical system, a CNC machine, JGrafchart (described below) and an order system, each connected through a separate communication endpoint. The PLC system is connected via OPC, the CNC machine is connected via MTConnect, JGrafchart is connected via SocketIO and the order system is just a mock-up.

Grafchart is a graphical programming language which extends Sequential Function Charts (SFC), the IEC 61131-3 (IEC 2013) PLC standard language for sequential control (Johnsson 1999; Theorin 2014). SFC is supported by most industrial automation systems and is widely used in industrial automation. Grafchart has the same graphical syntax as SFC, with steps and transitions, and adds high-level features for hierarchical structuring, reusable procedures and exception handling.

JGrafchart is a freely available Grafchart development environment, which supports service orchestration with web service technology (DPWS) (Theorin, Ollinger, and Johnsson 2013) and OPC Unified Architecture (Theorin, Hagsund, and Johnsson 2014). Unlike these technologies, event-driven control does not provide any built-in error handling to detect, for example, invalid requests. Hence, to know if a request was successful, an acknowledgement event is required. In the PLC communication endpoint, all writable variables generate an event when they change, which ensures acknowledgements for write requests.

Both JGrafchart applications and the IEC 61131-3 applications in the PLC are executed periodically. If events are allowed to arrive at any rate to these applications, pulse events might be missed. To avoid this, the JGrafchart and PLC communication endpoints throttle the delivery rate of incoming messages according to the application execution rate.

An overview of production of an order in the demonstrator is shown in Figure 7. A production request from the order system spawns a procedure call in JGrafchart. The request also triggers the CNC machine to start producing. When the CNCing completes, the product enters the physical system controlled by the PLC. The product is then completed through a collaboration between the PLC, which handles the real-time control, and JGrafchart, which handles high-level coordination and control. JGrafchart reacts to variable change events, such as new sensor values, from the PLC and sends control requests to the PLC. When the production is completed, an event with the production log is sent.

A discussion about manufacturing views in relation to LISA is available in Theorin et al. (2015).

5. Industrial use

The LISA architecture and patterns have been developed by industrial and academic partners with the objective to be industrially applicable. It is inspired by international standards and established off-the-shelf solutions. One core aim of LISA is that it should be usable for any device and application.

One automotive industry partner has partly implemented their own version of LISA and is using it for both data acquisition and control in a new body-in-white plant. The LISA implementation has resulted in dramatic time savings when upgrading the production system or when introducing new products. Most devices are now connected to the ESB and send out events when their state changes. The main differences in this industrial implementation compared to LISA are that XML is applied

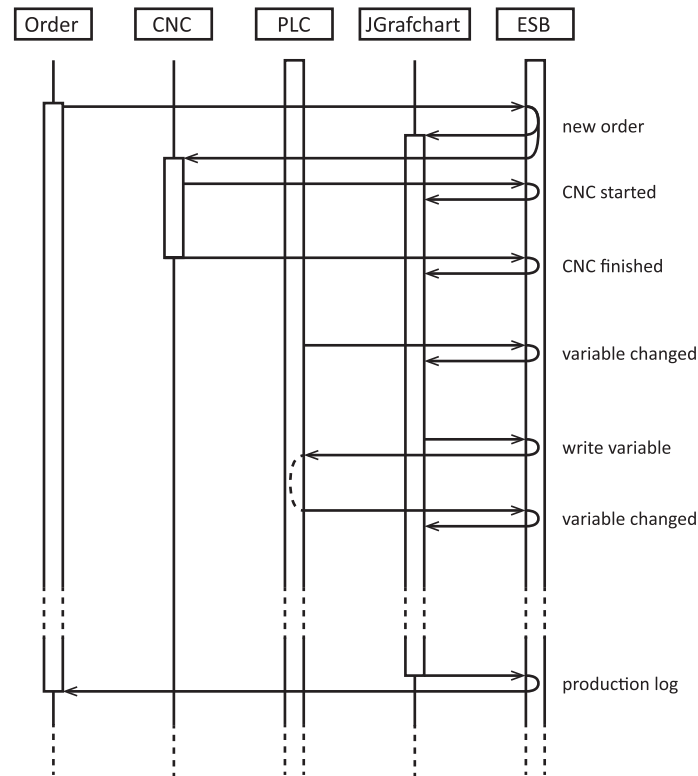


Figure 7. Production of an order in the demonstrator.

as a message format instead of JSON and that a commercial message bus is used instead of Apache ActiveMQ. The robots are directly connected to LISA, which makes it possible to monitor cycle times for robot stations and visualise the results in diagrams in real-time. Previously, a workstation sent predefined KPIs for each work cycle. With LISA, all communication is event-based on a finer granularity, and devices like PLCs, robots, product carriers, and operators send and receive low-level events which are then aggregated to get the desired KPIs.

The KPI calculation service has also been evaluated on historical data from another automotive industry partner. A large database with production events has been played back into LISA to evaluate services as well as performance. The data did not conform to the LISA message structure, but due to the flexible nature of LISA, events could be identified and generated.

The energy optimisation services are currently being evaluated at yet another automotive industry company where a real robot station is being optimised.

Since LISA is programming language independent, it is straightforward to integrate, for example, optimisers implemented in C with services implemented in Scala. This is a significant advantage for software development and maintenance.

6. Conclusions

LISA has been shown to be applicable for discrete manufacturing, for example, in the automotive industry, where processes are running asynchronously and the product flow is nonlinear. To validate interoperability, various industrial devices, software and programming languages have been used. Several industrial partners have been involved and have provided valuable feedback on the applicability of the research and permitted evaluation of the architecture. As a result, LISA is an event-based SOA which offers flexibility and scalability both for control of low-level applications and aggregation of higher level information, such as KPIs.

For the demonstrator, integration with LISA was straightforward. The advantages of the extreme loose coupling of EDA were also experienced. In particular, applications can be developed and tested in isolation, as other applications are easy to replace by mock-ups which simply produce events.

Improved visualisation for decision support and integration of online optimisation are future work.

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