An event-driven integrative framework enabling information notification among manufacturing resources

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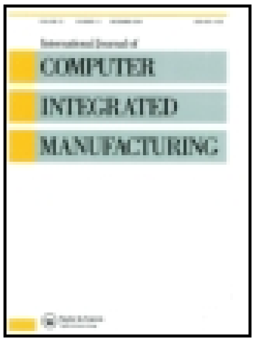

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ARTICLE

An event-driven integrative framework enabling information notification among manufacturing resources

G. E. Modoni[a], A. Trombetta[b], M. Veniero[c], M. Sacco[d] and D. Mourtzis[e]

[a]Institute of Industrial Technologies and Automation, National Research Council, Bari, Italy; [b]DiSTA, University of Insubria, Varese, Italy; [c]DISAMIS, University of Salerno, Salerno, Italy; [d]Institute of Industrial Technologies and Automation - National Research Council, Milano, Italy; [e]Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Rio Patras, Greece

ABSTRACT

Industry 4.0 paradigm envisions a new generation of collaborative manufacturing system where all the components are connected exploiting the Industrial Internet of Things (IIoT) protocol. Through this pervasive connection, sensors, machines, robots and other production equipment can communicate and share information with their surroundings resources. In order to contribute to realise such a vision, this paper introduces an event-driven framework that enables the interaction of heterogeneous distributed resources, according to the principles of Industry 4.0 paradigm. The overall aim of this research is providing new mechanisms to notify significant information produced within the factory towards enabled and interested production resources. In particular, combining various technologies such as IIoT, Semantic Web, and Multi-Agent based systems, the proposed framework allows the resources to be updated about changes occurred in their context. Under these conditions, the framework can be exploited in all the scenarios where the cooperation among resources is a strict requirement, thus contributing to support various ad-hoc services that drive modern factories towards a more sustainable, efficient, and competitive manufacturing system. Moreover, the validity of the framework is demonstrated leveraging the implementation of its instance within a real case study.

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Introduction

Under the push of Industry 4.0 paradigm, modern manufacturing companies are dealing with a significant digital transition, with the aim to better address the challenges posed by the growing complexity of globalised businesses (Hermann, Pentek, and Otto 2016). A basic principle of this paradigm is that products, machines, systems, and business are always connected to create an intelligent network along the entire factory's value chain. According to this vision, manufacturing resources are being transformed from monolithic entities into distributed components, which are loosely coupled and autonomous but nevertheless endowed with networking and connectivity capabilities enabled by the increasingly widespread Industrial Internet of Things technology. Under these conditions, they become able to work together in a reliable and predictable manner, collaborating in a highly efficient way. Within this relationship of synergistic collaboration, the involved resources can exchange with each other relevant information about the evolution of their context. Each resource can elaborate this received information to take decisions and trigger actions, in response to specific external variations (Alexopoulos et al. 2016). Interesting examples of these resources are self-organised logistics or production machines that can react to changes occurred in their surrounding context. Such a model of 'social' and context-aware resources can contribute to the realisation of a highly flexible and responsive manufacturing system and this realisation is a particularly relevant goal for modern factories, as its inclusion in the scope of the priority research lines for the H2020 three-year period 2018–2020 demonstrates (Effra 2016).

An essential feature of these envisioned social resources is their capability to keep other interested surrounding resources updated about specific information (e.g. about their status, properties, and history, etc.). However, this feature is still far from its comprehensive implementation, even the actual state of the art highlights significant recent achievements that have made the manufacturing resources more integrated each-other. One of the major issues hindering this implementation is the limited capability of a large part of the resources distributed within the shop-floor to automatically interpret the exchanged information in a meaningful manner (semantic interoperability) (Atzori, Iera, and Morabito 2010). This issue, mainly due to the high heterogeneity of data model formats adopted by each different resource (Modoni et al. 2017a), has been addressed in this research work with the overall aim to explore and identify a model of collaboration among production resources. The main outcome of the research is the Virtual Integrative Manufacturing Framework for resources Interaction (VICKI), a potential reference architecture for a middleware application enabling notification of relevant information. Specifically, VICKI provides a technological infrastructure offering an event-driven mechanism that dynamically propagates the changing factors to the interested devices. To overcome the problem of the limited interoperability among the connected resources, VICKI leverages a publish-subscribe middleware where requests of subscriptions

CONTACT G. E. Modoni ✉ gianfranco.modoni@itia.cnr.it

and corresponding notifications are expressed according to a common data model. The latter is based in turn on the Semantic Web technologies (SWT) (Berners-Lee, Hendler, and Lassila 2001) and allows to virtualise the factory world providing a unified understanding of the vocabulary adopted by the distributed resources during their knowledge exchange. Moreover, this virtualisation of the overall manufacturing system is empowered in VICKI by the adoption of an agent-based system, which contributes to hide and abstract the control functions complexity of the cooperating entities.

In addition to the framework, a second significant outcome of this research consists in an implementation of a new middleware adhering to the VICKI's specifications. This implementation is validated within a real case study, thus allowing to demonstrate the correctness of the overall proposed approach.

This paper is divided into six sections. After this introduction, Section 2 examines vision and motivations behind this work. Section 3 reviews the literature related to this research study, while Section 4 illustrates the framework and its five layers. Section 5 presents the implementation of an instance that has its root in the layers of the proposed framework. Finally, Section 6 draws the conclusions, summarising the main outcomes and pointing out some possible future works.

Research overview and problem statement

Motivations

Today's manufacturing systems consist of a broad collection of various hardware and software components, ranging from different CNC machines, robots and PLCs to complex software applications. These components, distributed and connected through several communication protocols, are typically responsible for one or more specific activities. Each of them produces worthwhile information about different aspects of their mechanical machining, and this information can in turn be exploited by other resources. Indeed, manufacturing processes are flows of activity executions linked each other and information produced during any process can be the relevant input of a subsequent step. However, in traditional manufacturing systems, this information is typically shared through communication protocols that are proprietary, not standardised and based on specific data format. In such a context, the information exchange capabilities of resources are limited to vertical, closed silos. As a result, each resource has only a partial fragmented view of data produced by other working resources. Moreover, they do not have an efficient access to a holistic view aggregating data produced by the overall system. Under these conditions, the large part of relevant information produced within the shop-floor is underused for gaining relevant insights in near real-time, e.g. for detecting production problems such as faults and failures. In order to overcome this gap, it is crucial to explore and identify a valid information and communication system (ICS) capable to interconnect and synchronise the resources of a manufacturing system. In particular, as behaviour and operations of the IIoT resources can heavily depend on changes of state occurring within other connected resources, it is essential that this envisioned ICS has the capability to notify these variations among interested resources. Thanks to this capability, each resource can send messages, for example, whenever a product changes position, or when a machine finishes its work.

The herein presented work goes in this direction, with the aim of conceiving, designing, realising, and demonstrating a framework for such an ICS. In particular, the idea behind this work is that this framework can be taken as a reference solution by companies interested to make their resources more interoperable and thus better able to communicate significant data to other resources. This way, each resource can have a holistic view about chain information, so that its decisions can be taken according to business and operational context variations. The dynamic and distributed nature of the new manufacturing system's model leveraging the Industry 4.0 principles can provide a valid contribution to conceive and realise such a framework. Its realisation requires the rethinking of the architecture of the traditional distributed systems towards a solution that enhances interoperability by mediating and reconciling differences in meaning of the exchanged data among the involved resources (Blair et al. 2011). In addition, the conceived framework must harvest near real-time data, which can be captured, analysed and transformed into relevant insights in order to be then distributed to interested resources. For this reason, efforts should particularly address big data management, i.e. data sets so complex and large that they can be hardly supported by traditional software tools (McAfee, Brynjolfsson, and Davenport 2012).

In summary, the efforts of the study are addressed to look for an answer to the following **research questions**:

- **Which framework should be adopted by a manufacturing company to enable a notification of relevant information among the production resources?**
- **Which technologies should be adopted to overcome the resources interoperability issue hindering this propagation? How the selected technologies can be integrated within the framework?**
- **How and to which extend can this framework be applied in real scenarios?**

Motivating scenario

The following scenario highlights the motivations behind this study.

In a factory plant which produces electronic assembled components, the production layout is composed of several working stations which can perform different operations (e.g. drilling, milling, etc.). In addition, the product components can undergo various operations performed in the same or different working stations following a specific order. For this reason, each product component is placed on a different pallet to be transported along the production line through a conveyor system. To make this process more effective and efficient, it is important to automatically move the pallets towards the closest available working station, leveraging information concerning the availability status of all the working stations.

To achieve this goal, it is essential to monitor and optimise the position of various pallets along the conveyer belt by enhancing the manufacturing system by means of indoor localisation and route analysis functionalities. Thus, various kind of devices and services were recently installed across the shop-floor. The installed technological components comprise (Figure 1): a) a set of *smart sensors* monitoring the pallet position; b) *Optimiser*, a simulation tool which elaborates the pallet position and the availability status of the working stations with the goal to identify the optimised pallet route; c) a set of *smart actuators*, connected to the carriages, which allow to change the route of the pallets along the conveyor belt; d) *Nearest Services*, a service providing the list of the nearest available factory's services, based on the position of the pallet. Data acquired by the sensors must be sent through a message or event to the *Optimiser*, which must calculate the best route for each pallet. If a pallet route is considered optimisable by the Optimiser, this information should be notified, through a specified message or event, to the actuator linked with the carriage transporting the pallet.

This scenario advocates the need for a kind of solution for synchronisation and cooperation among the various involved components. In particular, it is desirable a smart mechanism that monitors the information produced by the pallet, captures eventual events and notifies alarms to interested data consumers (e.g. the actuators), which in turn react somehow.

Framework requirements elicitation

To define key aspects of the framework and empower its conception, a set of its main requirements is reported in the following.

R1: Connection to the resources of the real factory. The framework has to support the connection to different real resource, each one characterised by a specific communication protocol.

R2: Flexible registration of the consumers to relevant information. Information consumers must be able to register for specific events, expressing the information contents they are interested in (e.g. temperature of a working machine) under the form of flexible subscription requests.

R3: Notification of information update. Each resource, after having gathered the information which oversees (e.g. a change of temperature within a working station), keeps the other interested surrounding resources updated about occurring events. The updates are expressed in messages where semantic differences among information consumers and producers are resolved.

R4: Events persistence. Each information authored by a resource must be retained in order to be at any time made available to any consumer that notifies its interest to receive this information.

R5: Consumers events reactions. Consumers can make some evaluations of the received information and then, if needed, take some actions to be applied to the real factory.

R6: Scalability. The architecture of the framework must adapt to the business needs, thus upscaling or downscaling according to specific variations (e.g. the change in the number of consumers or in the number of their subscriptions, etc.).

R7: Near real-time processing. The framework must support near-real-time services, allowing structured and unstructured data produced from distributed resources to be processed in an efficient manner.

R8: Automatic reasoning. Part of the data coming from the real factory are not ready to support the decision making process. This is the reason why these data must be processed in order to extracti relevant insights.

Research background and industrial references

This section aims to provide an updated state of the art on major areas of the literature that are particularly relevant to understand the challenges of this research study. In particular,

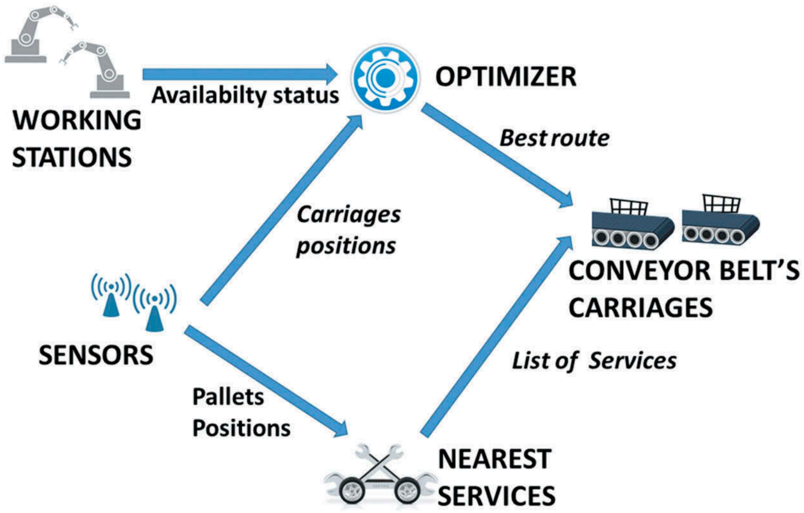

Figure 1. Overall workflow of the motivating scenario.

for each area, it is reported an overview of the major references in the fields of the scientific and industrial research that have been taken into account, highlighting also the features that distinguish the mentioned references from the herein presented approach.

Frameworks for manufacturing resources cooperation in the era of Industry 4.0

The popularity of Industry 4.0 paradigm has grown very rapidly in recent years among manufacturers and academics, creating the conditions for a new industrial revolution (Lasi et al. 2014). Unlike preceding three industrial revolutions which were driven by a single-specific technology (e.g. steam, electricity, etc.), this fourth industrial revolution is based on the combination and interaction of a plethora of existing and new technologies around the concepts of IIoT and CPPS (Leitão et al. 2016). In addition, these technologies are linked all together according with the following six Principles: Interoperability, Virtualisation, Decentralisation, Real-Time Capability, Modularity, Service Orientation (Hermann, Pentek, and Otto 2016). This heterogeneous mix of technologies adds complexity to the digital world of the factory and for this reason they need to be adapted and rethought in order to address the requirements coming from complex scenarios. Specifically, in order to fully unlock their potential, various existing ICT solutions have to be integrated and adapted to the industrial needs, and then deployed within the shop-floor. In this regard, it is essential to define ad-hoc architectural framework in order to clearly highlight the concepts and relationships resulting from the new perspective proposed by the Industry 4.0 paradigm.

In the field of manufacturing system, one well-known framework already available in literature is the 5C architecture for Cyber-Physical Systems (Lee, Bagheri, and Kao 2015). This architecture is intended to provide a step-by-step guideline for developing and deploying a CPS for manufacturing application. It is layers-based and includes the following levels: 'Smart Connection', 'Data-to-information Conversion', 'Cyber', 'Cognition', 'Configuration'. The 5C architecture can be a valid reference model for the herein presented framework, despite it should be significantly extended since it has the limitation that it has not been conceived to enhance interoperability among resources.

Another valuable architectural model is the Reference Architecture Model for Industry 4.0 (RAMI 4.0), which is designed to map and classify any Industry 4.0 based component of Industry 4.0 (Hankel 2016). RAMI 4.0 is based on a three-dimensional coordinate system. The right horizontal axis represents the hierarchy level of a generic object within the factory world; this object can be the manufactured product, a component of a machine, a machine, up to the 'Connected World'. The left horizontal axis embodies the life cycle of facilities and products. The vertical axis is divided into six layers in order to describe the decomposition of a machine into its properties. These Layers are business, functional, information, communication, integration and asset.

Frameworks for ICS

Another key-point related with the exploitation of the Industry 4.0 technologies and also relevant for this research work is the need of standardised framework enabling the realisation of valid ICS.

The traditional approach of ICS to connect applications is based on a Point-to-Point (PtP) integration exploiting the client/server pattern (Yao et al. 2018). However, the number of connections within such a system can increase quadratically with the number of involved applications and this issue makes the system rigid and not easy to maintain. An alternative solution for ICS is an event-driven system that is endowed of a loosely coupled and highly distributed architecture and thus it can offer better context awareness and a real-time responsiveness. An event-driven management approach was studied to support a framework based on RFID for integrating planning, scheduling and control as a whole, and solves the dynamic scheduling problems (Yao et al. 2018). However, the implemented demonstrator is based on RFID technology and the potential of the proposed framework in other manufacturing scenarios should be still investigated.

Another event-driven approach is capable of adapting to the dynamic variations exploiting real-time monitoring data from production shop-floor (Mourtzis et al. 2016). Also, Line Information System Architecture (LISA) is an event-driven manufacturing information system framework which has been developed for Industry 4.0 to integrate devices and services of the factory (also called the Tweeting Factory) (Theorin et al. 2017). Messages (tweets) from any device are sent and transformed into knowledge that is used for online monitoring, control, and optimisation. This solution provides an adapter for each device and for each new device it is needed a new adapter that performs the mapping between the device's data format and the common data format. Instead, the adapter is not needed in the solution herein proposed, since events producer e consumer use a common and shared model.

Available solutions of ICS in modern manufacturing tend to lack the capability to favor the interoperability among the different connected devices (Yao et al. 2018). Indeed, since the developments based on the Industry 4.0 paradigm are characterised by a large heterogeneity in terms of adopted technologies, the resources involved in a manufacturing system have reduced capabilities to cooperate and interact each-other at high-level (Modoni et al. 2017a). Moreover, the lack of widely accepted standards contributes to worsen an already messy scenario. Under these conditions, these resources do not have an adequate level of semantic interoperability (Atzori, Iera, and Morabito 2010) and such a condition can cause the isolation of a significant set of data and enlarges the problem of 'too much data and not enough knowledge' (Sheth, Henson, and Sahoo 2008). In addition, the involved resources can lose, during their interactions, the implicit information concerning the meaning of exchanged data (Gyrard, Bonnet, and Boudaoud 2014).

The following section discusses the major technologies to enhance semantic interoperability.

Architecture and technologies to enhance interoperability among resources

A significant contribution to enhance interoperability among resources can be provided by a middleware application, which is a layer that acts as 'software glue' between applications, operating systems and network layers (Atzori, Iera, and Morabito 2010). In particular, among the several types of available middleware, an efficient solution to support ICS is offered by the technologies based on the publish–subscribe interactions. In fact, they will adapt to the needs to synchronise the changing information among decoupled components distributed within an IoT network (Ali et al. 2015). However, to the best of the knowledge, solutions of middleware currently available in the literature provide only static methods of selection of the information to be subscribed. Typically, these methods are based on predefined syntactical subjects (Fortino et al. 2013), while they do not consider different flexibility and expressivity requirements, normally needed to support complex scenarios widespread in the manufacturing field (Moser et al. 2009; Modoni et al. 2017b; Razzaque et al. 2016). This lack is also evident in the standard communication protocol OPC UA (Leitner & Mahnke, 2006), whose last specifications provide a publish-subscribe middleware through which clients can subscribe to a specific tag and be notified and informed when the tag's value changes (OPC UA 2017), but they does not provide semantics capabilities.

A potential approach to enhance semantic interoperability is defining and representing the shared knowledge of the involved resources through a common model specified leveraging the SWT. Such an approach based on SWT is proposed in (Gyrard, Bonnet, and Boudaoud 2014) with the aim to ease integration among cross-domain applications, through the combination, enrichment, and reasoning concerning Machine to Machine (M2M) communication data. The potential of the semantic-based approach has been also investigated in the context of Virtual Factory Framework (VFF) project which aimed to enhance the semantic interoperability of different software applications supporting the entire lifecycle of the factory, so that these applications can share and exploit the same information (Kádár, Terkaj, and Sacco 2013). In such a scenario, SWT have been adopted to formally describe this information in a semantic model, which provides a holistic view of the factory as a whole, considering resources, processes, product and their coevolution over the time (Tolio et al. 2010). A semantic model is also one of the pillars for the herein presented study. Indeed, the idea behind it is that a semantic model, always synchronised with the real factory, can be a valid basis to realise the semantic enhancement of the middleware, thus contributing to bridge the above-mentioned lack of semantic capabilities of the traditional publish-subscribe middleware. This approach will be studied in deep in Section 4.

In order to enhance cooperation among components of an IIoT network, another possible way is conceiving the network as a distributed cooperative system based on agents. In such a context, behind each production resource, there is a specific agent which manages its collaborations. The agent proxies the functions of the corresponding resource and then can cooperate with other agents to proactively collect data and update the current state of the system. Multi-agent based technology had been applied in the past in different fields (e.g. telecommunications, healthcare, manufacturing, etc.) (Dilts, Boyd, and Whorms 1991). One of the first agent-based solution proposed in the manufacturing field is the holonic manufacturing (Van Brussel et al. 1998), represented by holarchies of autonomous, cooperative entities (holons) that can embody any manufacturing.

On agent technologies, it is inspired the architecture proposed by the research project UBIWARE (Katasonov et al. 2008), which realised a middleware for the IoT to support the creation of a self-managed system comprising a set of distributed and heterogeneous components of different nature. More recently, an agent-based system is introduced in (Wang et al. 2016) where it is proposed an intelligent negotiation mechanism for agents which can cooperate with each other. In (Rocha et al. 2014) it is illustrated another agent-based framework for manufacturing systems which provides the latter the capacity to quickly adapt and reconfigure, allowing to cover the plugging and unplugging of production resources as well as the adjustment of parameters during production activities.

Multi-agent based solutions in combination with SWT have already been used in the ADACOR architecture, which is developed as a set of autonomous, cooperative holons, each of them represents a specific manufacturing component (Leitão and Restivo 2006). Another interesting combination of semantic model and multi-agent technology can be found within the Java Agent Development (JADE) framework (Bellifemine, Caire, and Greenwood 2007). However, this framework uses a proprietary semantic model. In addition, JADE uses only semantics for the provided vocabulary and the syntax checking, while the adoption of a semantic model can bring the significant advantage of creating a cognitive model with reasoning capacities (Lemaignan et al. 2006). Moreover, the exchange of semantic messages in JADE is based on a restrict meta-model which comprises entities such as Concept, Agent Action and Predicate. Due to the fact that these messages are FIPA compliant (FIPA 2008), JADE agents can interact with other agents, which can be also agents managed from other FIPA frameworks different from JADE. The combination of semantics with JADE can be found within the project GRACE. In such a context, the asynchronous communication among distributed agents included also the content meaning of the exchanged messages, which were standardised according to the GRACE ontology (Leitão et al. 2015).

As seen above, the three technologies of middleware, SWT and multi-agent systems have been separately (and sometimes two in combination) studied in several research works to enhance interoperability. The distinguishing key-feature of the herein presented approach is that it combines and overlaps these three technologies within a holistic framework, with the overall goal to enhance interoperability among the producers and consumers of an event-driven system. This framework is described in the next section.

Virtual Integrative Manufacturing Framework for Resources Interaction (VICKI)

In response to the first research question posed in Section 2.2, this section proposes VICKI, an integrative framework to develop the architecture of a middleware that satisfies the requirements elicited in Section 2.4. In particular, VICKI enables a proper interaction of the production resources, enhancing their capability to propagate the information related to changes of state occurring in their context towards other interested resources. Moreover, in order to address the second research question, the section reports how the three major technologies (messages oriented middleware, semantic web, agent technologies), adopted to overcome the interoperability issue among information consumers and producers, are integrated into the framework.

An overview of the framework

VICKI is a multi-agent and semantic-based framework providing near real-time signalling capabilities to all the networked enabled resources involved in a manufacturing system. It follows a hierarchical architecture structured on the following five main Layers (Figure 2): 1) **Real Factory**; 2) **IoT Hub**; 3) **Publish-Subscriber Middleware**; 4) **Reasoner**; 5) **Digital Twin**.

Leveraging these layers, VICKI allows to distribute new emerging information to interested resources deployed in the shop floor (**Layer 1, Real Factory**), which can register themselves to be notified about the changes of the state of one or more interesting elements of the shared knowledge. Heterogeneous data coming from the **Real Factory** are sent over a cloud-based platform (**Layer 2, IIoT Hub**) where these data are processed to gain useful insights. The cloud platform guarantees the horizontal scalability of the overall architecture; it also exposes various functionalities as micro-services. The evaluation of the emergence of new interesting information is continuously performed by a middleware (**Layer 3, Publish-Subscribe Middleware**), capable of recognising an update of the knowledge-base and of notifying eventual updates to subscribers interested in information. The value and the capabilities of physical resources are augmented through their virtualisation, achieved in the form of a digital model **(Layer 5, Digital Twin)** that can be synchronised with the **Real Factory**. Leveraging the SWT, the **Digital Twin (DT)** explicitly defines the semantics of the factory's objects by taking as a reference a model that all the resources share.

In addition, this information handled by the DT is near real-time elaborated by the **Stream Reasoner (Layer 4)**, which can take some preventive or corrective decisions to be applied to the **Real Factory layer**, thus closing the loop between the Real and Virtual world. Under these conditions, a circular data process is generated, where data flow from physical resources to analytic systems, and then return back to the physical resources in the form of control feedbacks.

It is expected that the adoption of the proposed framework within a manufacturing system can bring various advantages. The most significant are the following:

- **Enhancement of the semantic interoperability** of the productive resources, which also contributes to abstract their complexity, thus simplifying their interactions.
- **Complete decoupling of the event producers from events consumers**, thus overcoming the limitation of traditional middleware solutions to support flexible cooperation mechanisms among producers and consumers.
- **More efficiency** in terms of network use compared to a polling-based solution, since data are sent only when change.
- **Simplification of the design** and **deployment of the overall architecture**, since VICKI is built on the basis of several building blocks.

The layers

This section explores in details the layers of the VICKI and in particular how they are conceived to meet the requirements reported in Section 2.4. In the following, the latter are reported highlighted in brackets in bold whenever they drove important architectural decisions.

Layer 1: real factory

This layer is responsible for the collection of significant data from production resources. In this regard, different kind of sensors are distributed in the shop-floor to measure properties from the real world. At this level, the data can be semantically enriched in order to enclose their meaning. This enrichment can be carried out through a conversion process from the legacy model to the semantic model (Modoni et al. 2017a). Afterwards, the data can be sent under the form of telemetry

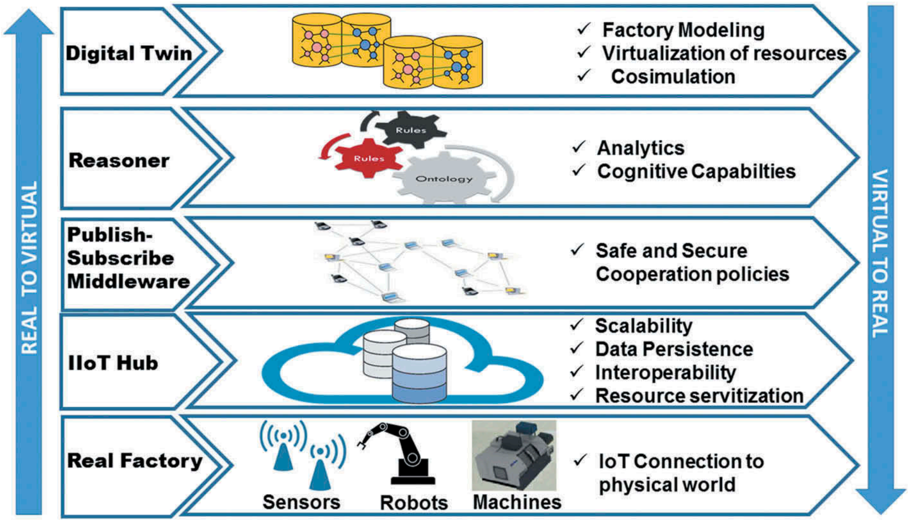

Figure 2. The five-layers of VICKI.

data flow from the real to the virtual factory (Modoni, Sacco, and Terkaj 2016).

Layer 2: IIoT Hub

This layer plays the role of central hub where information gathered from every machine connected to the network are collected, persisted and processed **(R4)**. In the VICKI context, the importance of cloud computing lies in its capability to provide scalable and decentralised information processing and data management capabilities (Adamson et al. 2017) **(R6)**. Any database hosted on the cloud to persist the data coming from the shop floor can fully exploit this capability. In fact, the cloud automatically virtualises the available hardware and software resources (e.g. nodes of the server) thus scaling up and down depending on the load of the system. In addition, cloud technologies expose value-added services that can be accessed globally via the Internet (Mourtzis & Vlachou, Cloud-based cyber-physical systems and quality of services, Mourtzis and Vlachou 2016). Indeed, all the devices including the legacy systems can provide/consume data to/from the shop-floor via the interface provided by the Cloud layer. This interface can support various protocols (like M2M, ZigBee, etc.), allowing to integrate different types of devices **(R1)**.

Layer 3: Publish-Subscribe Middleware

The Publish-Subscribe Middleware (PSM) acts as a connector mediating data exchanges between shop-floor event sources (publishers) and consumer services (subscribers). It provides a central point dispatching information through mechanisms that are transparent to its clients, leveraging an efficient event-driven model based on SWT (**Layer 5**). Indeed, a relevant feature of the PSM is its capability to express consumer requests and publisher updates according to a common semantic model **(R2, R3)**. Specifically, the requests are expressed in SPARQL (2017) and for this reason, the agents are required to know the SPARQL syntax and the T-BOX structure of the semantic model. In addition, the changed information is notified through RDF RDF (2017). In this way, the connected resources can cooperate synergistically on the basis of a semantic model through which the involved devices can share information. Figure 3 reports the information flows concerning this dispatching service.

PSM also enables a hardware independent interoperability of the consumers, thus allowing to support an easy integration of devices even if based on heterogeneous technologies (**R1**). As highlighted in Figure 3, any resource can act at the same time both as consumer of some type of relevant information and source of other types of information. This proposed solution is more efficient in terms of performance compared to a polling-based model. In fact, being consumers not constrained to poll data through continuous queries to be informed about data updates, the PSM can reduce the bandwidth cost of the semantic queries, as well as the required workload both at the client and server sides.

Layer 4: stream reasoner

This layer allows logical reasoning in near real-time on the data streams from the shop floor to entail and infer new knowledge about the main concepts represented in the Digital Twin (**Layer 5**) and thus extracting new insights (e.g. on the status of the machines) **(R7, R8)**. This capability, called stream reasoning, allows to better support the decision process of a large number of concurrent users (Stuckenschmidt et al. 2010).

The inferred knowledge can be then propagated through the PSM towards the interested resources which can use them to take some decisions to apply appropriate actions. The eventual corrective or preventive decisions that are taken have an impact on the **Real Factory layer**, thus closing the loop between the Real and Virtual world (Figure 4) **(R5)**. In order to realise this closed loop, the reasoning engine is

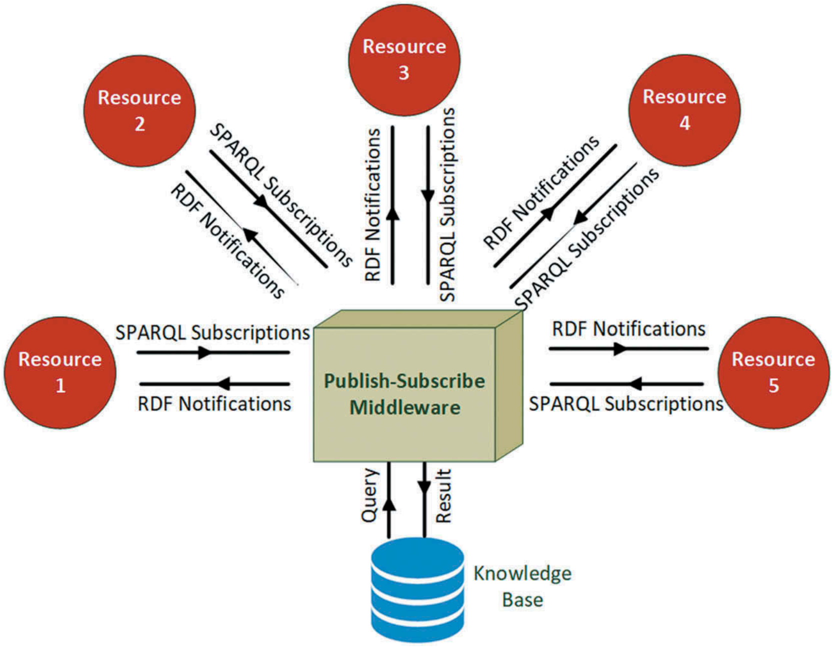

Figure 3. Semantic Middleware dispatching service.

paired with a set of inference rules, which are exploited for the automatic entailments. In addition, rules are formalised considering the meta-model representing the Digital Twin of the factory (**Layer 5**) (Figure 5).

Layer 5: semantic DT

Semantic DT is a digital image of the real world of the factory, representing its conceptual, structural and behavioural aspects, which are specified according to various levels of detail. In VICKI the DT is expressed in the form of a semantic model that explicitly defines the semantics of the represented factory's objects. This model is handled and persisted by a proper RDF Store (Modoni, Sacco, and Terkaj 2014) **(R4)**, a specific database which links and exposes the information through an ad-hoc service (SPARQL endpoint) and hosted on the **IIoT Hub**. This model is shared by all the distributed resources connected to the framework, thus providing a unified understanding of the vocabulary adopted by the resources during their knowledge exchange. In addition, DT allows to support the virtualisation of the physical resources in the form of virtual agents which can act on behalf of the corresponding real counterparts. However, the development of the semantic model for the DT is not dealt in this study as the model in this work is only a means to demonstrate the feasibility of the overall approach. For this reason, the applicability of a VICKI's approach is based on the assumption that an existing (or new one designed from scratch) semantic virtual model has been previously selected to explicitly define the semantics of the factory's objects.

VICKI adherence to Industry 4.0 principles

Table 1 highlights how the five layers of the proposed framework are linked to the Industry 4.0 principles and technologies.

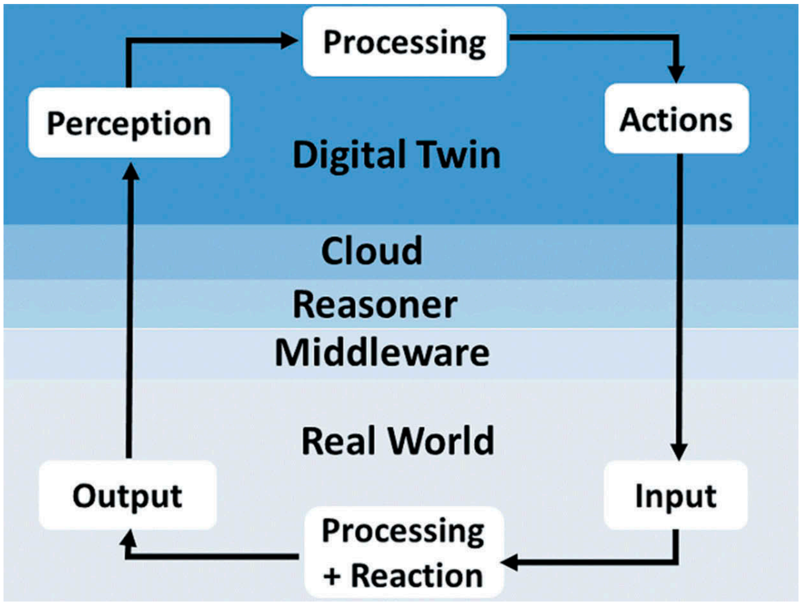

Figure 4. The closed Loop between Real and Virtual world.

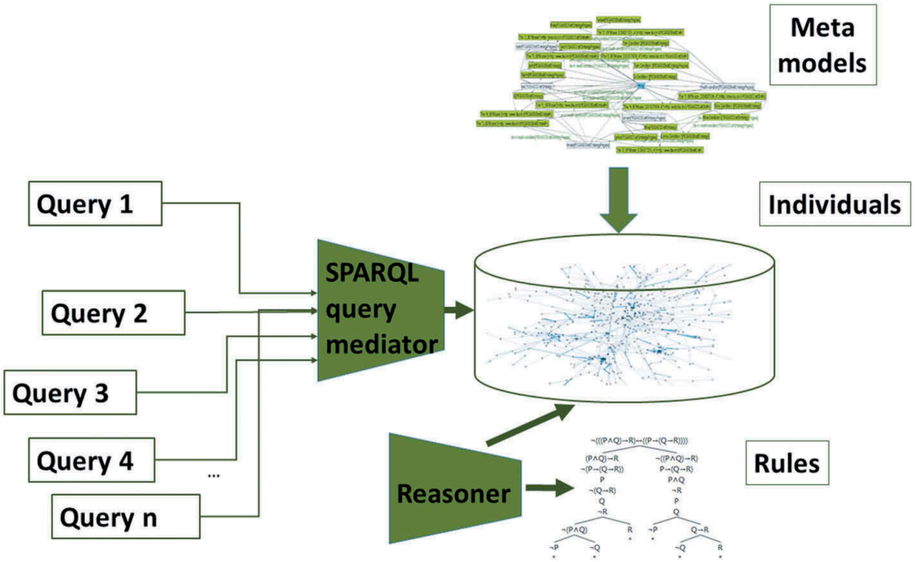

Figure 5. Semantic model querying and reasoning mechanism.

Moreover, regarding the VICKI adherence to Industry 4.0 reference models, it should be emphasised that the VICKI framework covers the overall model of the RAMI 4.0 along the three axes of the model, as it connects all the components across the whole factory lifecycle and for all the layers. In addition, VICKI provides a unified model for all the components (from product to Connected World) while there is a consistent data model (the semantic model) during the whole life cycle. In addition, VICKI supports the communication across all IT levels.

The pilot study

In response to the third research questions posed in Section 2.2, this section introduces the Semantic Event Notifier (SEN), a lightweight prototype of middleware that has its root in the VICKI architecture. Specifically, in order to assess VICKI's capability to support real scenarios, this section investigates the SEN's potential within the scenario reported in Section 2.3.

Application to the motivating scenario

Figure 6 points out the application of VICKI and its instance SEN within the described scenario. The sensors monitoring the pallet position play the role of publisher, as they have to share the information concerning the pallet position (Step 1). The working stations are also publishers, as they have to share their availability status (Step 2). According to the Publish-Subscribe middleware specifications, the information exchanged during these two steps is expressed in the form of a SPARQL UPDATE. This information can be then consumed by the simulation tool (Optimiser) which has previously subscribed to the changes applied to the pallet position (Step 3) and to the availability status provided by the working stations, with the goal to identify the optimised pallet route. In addition, the information concerning the route is then published (Step 4) and in its turn consumed by the IoT actuators to allow the carriages to change the route along the conveyor belt (Step 5). Finally, Nearest Services can consume the information concerning the pallets positions (Step 6) in order to compute the list of nearest services for each resource (Step 7).

The implementation and technology adoption

The sensors tracking the carriages positions, the working stations, the Optimiser and the conveyor belt's carriages are the main actors connected to the Physical Layer. Information authored by these resources is persisted into an RDF store (the Semantic Repository) in the form of semantic digital twin to keep track of the evolutions occurring in the Physical Layer (Rosen, von Wichert, Lo, & Bettenhausen, 2015). In this regard, the representation of the digital twin is mainly based on the Semantic Sensor Network (SSN) Ontology (Compton 2012). The adopted semantic repository is Stardog (Stardog n.d.), a commercial RDF store solution meeting the requirements typic of an intensive data scenario. Stardog includes a component which provides reasoning capabilities; this component represents a de facto implementation of the VICKI's Layer 4. Moreover, Stardog is deployed into Microsoft Azure (Microsoft Azure 2018), a cloud-based platform that guarantees the horizontal scalability of the overall architecture.

Through the publish/subscribe pattern provided by the Layer 3, clients can subscribe specifying their interest's profile, the type of expected replies and authorisation credentials. A valid starting point for the Layer 3's implementation had been a solution middleware validated in the field of AAL and presented in (Modoni et al. 2017b). Since the original solution did not meet the requirements R5, R6, and R7, this solution was also extended in order to meet these requirements. Figure 7 outlines the components in charge of implementing the Publish-Subscribe Middleware (Layer 3): Update Manager (UM) and Semantic Broker (SB). UM allows connected resources to affect the knowledge base through a web service exposed in the form of SPARQL endpoint provided by Stardog.

SB comprises on its turn the Subscription Manager (SM) and the Messaging System (MS). SM is the component which is always listening on the queue that manages the new subscription requests, leveraging a messaging system. The adopted solution of messaging system is Apache ActiveMQ™ (n.d.), an industrial state of the art open source messaging platform providing API in several popular industrial languages. The communication protocol for publish/subscribe implementation has been set to Openwire (ActiveMQ OpenWire n.d.) since this protocol directly supports private queuing.

MS is supported by the on behalf of the multi-agent system. The implementation of this multi-agent system relies on the JADE

Table 1. Links between VICKI layers and Industry 4.0 principles and technologies.

	Interoperability	Virtualisation	Decentralisation	Real-Time Capability	Modularity	Service Orientation
Layer 1: Real Factory			Ubiquitous Computing	Big Data, Factory-Telemetry		IoT
Layer 2: IIoT Hub			Cloud	NoSQL Database		
Layer 3: Publish–Subscribe Middleware	Messages Middleware				Multi Agent Systems	Web Services
Layer 4: Stream Reasoner	SWT				SWT	
Layer 5: Semantic Digital Twin	SWT	Multi Agent Systems		SWT	Multi Agent Systems	

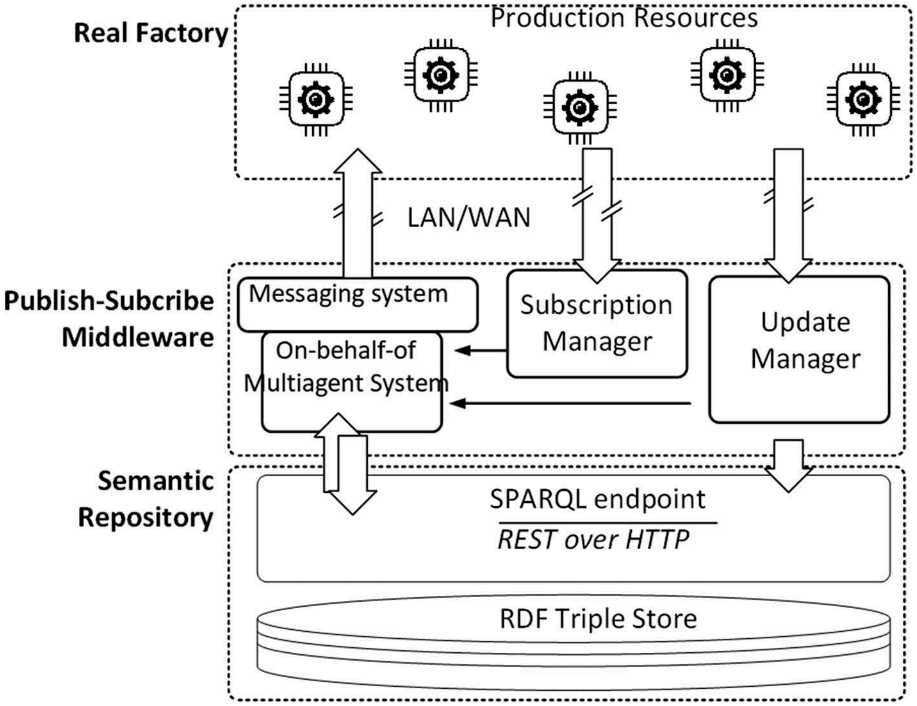

Figure 6. VICKI application within the motivating scenario.

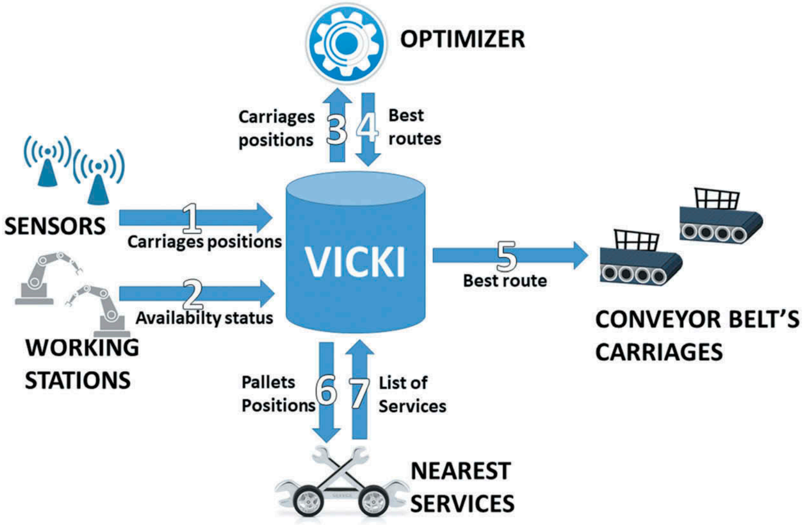

Figure 7. The overall architecture of SEN.

(Bellifemine, Caire, and Greenwood 2007), a middleware for the implementation of distributed and cooperating multi-agent systems. Among the other, the JADE Direct Facilitator (DF) component provides the functionality of yellow page service, which is one of the essential requirements of the VICKI framework. Whenever SM receives a new subscription request from a connected client, it activates server-side an 'on-behalf-of agent' which takes care of the client interests, signalling new emerging information to the consumer. In each moment, the consumer can unsubscribe by cancelling its request. When a resource authors new knowledge, the UM informs the SB of the occurred event so that, in a continuous query processing manner, the SB can evaluate new emerging information, and then notifies it to the consumer resource via the MS. The evaluation of the emergence of interesting information is proactively performed by a central semantic knowledge management agency at Layer 4 (the Stream Reasoner layer) that, intercepting updates to the knowledge-base (the DT Layer) through mechanisms that are transparent to the subscribers, notifies occurred changes to subscribers' interested information.

The main results of the pilot

This case study allowed to demonstrate the validity of the VICKI-based approach, showing that heterogeneous resources can be integrated and configured into an IIoT-based system to share knowledge through a system application that is based on the VICKI framework. The pilot highlighted a set of benefits, mainly in terms of scalability of the overall architecture. Specifically, it demonstrated that the implemented system is capable to support a high number of connected resources (up to 100) while sharing a large knowledge base (up 10^6 semantic triples).

Conclusions

This paper has explored a cooperative pattern for the interaction of distributed heterogeneous resources in the field of manufacturing, according to the principles of Industry 4.0 paradigm. A major result of this research is the VICKI, a reference architecture for a context-aware application which meets the requirements elicited in Section 2.4 and represents the response to the first research question of this study. The framework enables a model of communication and collaboration among manufacturing resources which allows to dynamically propagate the information changes occurred within the shop floor towards all the interested and enabled components. Moreover, in order to address the second research question, it has been described how the three major technologies (messages oriented middleware, semantic web, agent technologies), adopted to overcome the interoperability issue among information consumers and producers, are integrated into VICKI. Finally, in response to the third research question, it has been demonstrated the validity of the framework, assessing the potential of one its implementation in the real case study.

The exploitation of VICKI in manufacturing can enhance and integrate the orchestration of the services supporting the whole lifecycle of the factory, thus giving a significant contribution towards the implementation of a platform of interoperable services as provided by the Industry 4.0 vision. In particular, the framework functionalities can be exploited in all the fields where the cooperation among resources is a strict requirement. One of these fields is the intelligent production, where the framework functionalities can allow the new generation of smart products (Schmidt et al. 2015) to cooperate and collaborate with their surrounding environment. In order to connect a smart product to VICKI, it is necessary to model the product and its characteristics within the DT. In addition, it has to be implemented an agent that handles the product's connection towards the SM, and, through the latter, the product can exchange information on its lifecycle with the other production resources. Another field of application of VICKI can be the collaborative robotics where VICKI can be an enabling technology for the cooperation among robots and humans. In addition, the framework can be useful in other fields different from manufacturing (e.g. to support the interaction of autonomous cars). In fact, even it has been conceived for a manufacturing system, it is agnostic to the meta model of the used semantic data, and for this reason, its transfer technology in other fields is lightweight and can be done with little effort.

Future steps

Future studies and developments related with this work will mainly address four goals. The first goal will regard the exploration and implementation of a Trust model to enable reliable and secure interactions between trustworthy entities. For example, in the motivating scenario reported in 2.3, the actuators must be sure that sensors monitoring the position of the pallet are trustworthy before consuming these data. In this regard, a potential solution of Trust model is based on the evaluation of the devices reputation, so that only the devices that are granted can publish critical information. The second goal is linked with the first one and will concern the identification of a valid pattern of edge-level processing to filter the noise, remove the corrupted data and aggregate information, thus contributing to minimise the congestion of the network. Moreover, while the current implementation assumes that there is a semantic meta-model shared between the different devices, the future implementation will investigate the capability to allow each device to have its own semantic model, leveraging modules for ontological alignment of different models. Finally, the fourth goal will regard the optimisation of the queries execution, through a smarter organisation of the meta-model based on a subdivision in different graphs. This way, when a change is triggered, the system will reload only the queries involving the graphs affected by the changes.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

D. Mourtzis http://orcid.org/0000-0002-7923-7363

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