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Abstract

Towards a Framework for Interoperable and Interconnected CPS-populated Systems for Proactive Maintenance

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***Abstract*— Cyber-Physical Systems (CPS) are creating new market opportunities and business models for all kind of European Industries. CPS-based platforms are increasing in their size and target application areas in a steady manner. However, even if progress is made every day supported by continuous technological advancements, CPS application and deployment is still challenging. Many solutions have been made available or is currently under development in several research projects/ initiatives. Typically, these solutions show no interoperability between each other and are tailored to a specific application context. Thus, there is an urgent need for a clear definition of what a CPS-populated system actually is. This will provide a common ground for designing and building interoperable CPS-populated systems. Interoperability represents one of the most challenging problems for such systems essentially due to their intrinsic characteristics: heterogeneity, distribution and networked. These must be addressed to allow the cooperation and collaboration between all the actors of the system. In this landscape, the MANTIS project is aimed to provide a reference model for interoperable and interconnected CPS-populated systems for maintenance-related ecosystems, which is the focus of this paper.**

Keywords—Cyber-Physical Systems; Service Orientation; MIMOSA; Interoperability

I. INTRODUCTION

The wider dissemination of intelligent devices in all aspects of human life is producing extremely complex environments that are, in turn, characterised by heterogeneity and distribution. The next wave in this era of computing envisions the active presence of physical objects/entities on the network [1]. As explained in [2][3], current technological advances are radically changing the way systems in different domains are designed and deployed, monitored and controlled. Especially the CPS approach is opening the doors to a new generation of systems, where information transparency, efficient and effective management, high availability, adaptability and (re-)configurability of assets and resources are the key characteristics.

As stated in [4], three main converging streams are pushing enterprises into the world of "smartness & connectivity". One of them – smart embedded systems, mobile services and pervasive computing – is contributing to the establishment of a cyber space [5] where data coming from assets and resources can be potentially used to: i) enable more and more exclusive, efficient and sustainable systems to assure a more efficient and effective management of the resources; and ii) create new and powerful business opportunities through the tighter integration of all the steps/stages of the product lifecycle management (PLM), and the provisioning to the customer of new product-service solutions [6].

As stated in [7]: *"Through CPS, the development of new business models, new services are expected which may change many aspects of our life"*. Nevertheless, CPS are becoming critical to the business success of many enterprises as confirmed in [8]: *"In transportation, manufacturing, telecommunications, consumer electronics, health and medical equipment, and intelligent buildings the value share of electronics, computing, communications, sensing, and actuation is expected to exceed 50% the end of the decade"*. However, CPS application and deployment is still challenged by set of technical, institutional, and societal issues.

This paper presents how the MANTIS project is building interoperable and interconnected CPS-populated systems for proactive maintenance for enabling service-based business model and improved asset availability at lower costs through continuous process and equipment monitoring and analysis.

II. THE MANTIS PROJECT

A. Challenges in CPS-populated Systems

Nowadays, conventional systems and processes are evolving into CPS. As stated in [9], the term "Cyber-Physical Systems" have been coined in 2006 and specifies a system consisting of computational, communication and control components combined with physical processes [10]. This definition indirectly points out the core elements and/or characteristics of a CPS, extended from [11], [12]:

- Enhancement of physical entities with Cyber capabilities;
- Networked at multiple and extreme scale;
- Dynamic behaviour (plug and unplug during operation);

- High degrees of automation, the control loops are typically closed;
- High degree of autonomy and collaboration to achieve a higher goal; and
- Tight integration between devices, processes, machines, humans and other software applications.

The elements and/or features of a CPS intrinsically identify a set of research challenges that need to be addressed to accelerate the progress and deployment of CPS in real application context. The research challenges here summarized are the ones related with the MANTIS project ambition and clustered according to [13]:

- Science and engineering foundations: a reference architecture for interoperable and interconnected CPS-populated systems in cross-sector applications;
- System performance, quality and acceptance: to create large, adaptive and resilient networked systems that are capable to operate in the specific environments where the physical entities are installed while delivering the required functionality in a reliable way; and
- Applied development and deployment: to provide methodologies for virtualization of physical entities and integration of heterogeneous systems. To deliver technology foundation for building interconnected and interoperable CPS-populated systems.

B. *The MANTIS Vision*

The overall aim of the MANTIS[1] project [14] is to develop platform for interoperable and interconnected CPS-populated systems for proactive maintenance ecosystems, i.e. for facilitating the implementation of predictive and proactive maintenance strategies. The MANTIS platform will provide a practical mean for implementing collaborative maintenance by taking advantage from:

a. the omnipresence of intelligent devices – that combine physical entities with computational and communication capabilities – in modern processes, machines and other distinct application domains; and
b. the maturity level reached by cloud-based infrastructure, as well as, the huge amount of computational and storage resources that are available and usable "on-demand".

Intelligent devices are the ones directly connected and/or installed to the physical resources and assets. They can potentially optimize and improve current maintenance activities and their related management systems by providing (often live) data – gathered during operation – that can be analysed (low level data analysis) to understand the behaviour of the related physical resources and assets. Furthermore, the data gathered from physical resources and assets can be also combined and analysed globally (high level data analysis) by using computational resources and complex algorithms running over the cloud (high level) to understand the collective behaviour of group of resources and assets. Therefore, within the MANTIS platform the data extraction, transforming, loading and pattern analysis will take place at different levels, namely (see Fig. 1):

Fig. 1 MANTIS overall concept idea and data processing levels

a. Low level: extraction, transforming, loading and analysis of simple signals to model and understand the behaviour of selected physical resources and assets.
b. High level: extraction, transforming, loading and analysis of complex data – typically the results of the low level – to model and understand the global behaviour of physical resources and assets.

Since data sources are typically characterized by distribution, heterogeneity, and a high degree of dynamicity (e.g. data sources like sensors can be plugged and unplugged any time), then the design of the MANTIS architecture has been driven by the following main requirements:

1. Integration of complex and heterogeneous large-scale distributed systems from different application domain; and
2. the design of CPS-populated systems to enable collaborative proactive maintenance strategies.

It is easy to understand that the design of interoperable and interconnected CPS-populated systems become a key element of the MANTIS implementations to allow to dynamical and on-demand addition or removal of data sources in/from the MANTIS platform to gather most of the maintenance relevant information automatically from the environment.

III. Related Works and Supporting Concepts

A. *ATHENA Project*

The ATHENA [15] was an EU-funded R&D project that aimed to provide the most comprehensive and systematic approach to remove barriers to interoperability. It aimed to enable interoperability between networked enterprises by structuring and delivering a comprehensive interoperability framework. The ATHENA Interoperability Framework (AIF) is structured in three parts, namely: i) Conceptual Integration; ii) Application Integration; and iii) Technical Integration; and addressed the interoperability problem at four levels: data/information, services, processes and enterprise/business.

The AIF provided the necessary baseline and fundamental theoretical foundation for structuring the MANTIS-Interoperability Framework (-IF). However, even if the structure of the AIF is applied in the MANTIS-IF, the latter is

[1] http://www.mantis-project.eu

particularized for the CPS domain. On the same direction, the four interoperability levels envisioned in the AIF are – in the MANTIS-IF – attached and organized according to the device/CPS application and communication features.

B. IoT-A Project

The Internet of Things – Architecture (IoT-A) [16] was an EU-funded R&D project that aimed to design and define an architectural reference model and related reference architecture for IoT-based systems. The IoT-A Architectural Reference Model (ARM) was an effort to handle the emergence of a variety of communication solutions and plethora of a cost-effective, rapidly evolving connected devices.

The IoT-A ARM delivered several models and guidelines to enable and promote interoperability at the communication level, as well as, at the service and the information level. Thanks to the similarities of the IoT and CPS research domain, and to the fact that the CPS domain is laying the foundation for the "creation of an Internet of Things, which combines with the Internet of Services" [17], the models and some guidelines of the MANTIS-IF are directly inspired by the IoT-A ARM.

C. Arrowhead Project

The Arrowhead [18] was an EU-funded R&D project that aimed to provide an intelligent middleware to allow the virtualization of physical assets into services. It includes principles on how to design Service Oriented Architecture (SOA)-based systems, guidelines for its documentation and a software framework capable of supporting its implementations. The design guidelines provide generic "black box" design patterns on how to implement application systems to be Arrowhead Framework compliant. Moreover, it already solves relevant issues regarding interface, protocol and semantic interoperability.

The Arrowhead project delivered a framework that has been used and deeply studied within the MANTIS-IF for enabling the technical integration as shown in section IV.

D. Focusing on Standards: MIMOSA

To achieve useful maintenance procedures and strategies information from large numbers of smart devices and systems needs to be collected and analysed. In this scenario, standards provide a set of terms, concepts, data formats, document styles and techniques so that the information collected can be easily processed by data analytics tasks and routines within different computer program. Thus, the provisioning and usage of standard models is a fundamental step to achieve interoperability.

The Machinery Information Management Open Systems Alliance (MIMOSA) open standards enable collaborative asset lifecycle management. It provides two open standards:

- Open System Architecture for Condition Based Maintenance (OSA-CBM): focused on facilitating the information acquisition processes.
- Open System Architecture for Enterprise Application Integration (OSA-EAI): focused on supporting integration between application at enterprise level.

If from one side the MIMOSA standards support a large range of asset management data types that allow them to be used in many asset management integration processes. From the other side they are complex, intricate and not well-documented. The MIMOSA standards are still immature. This lack of maturity makes the process of building and maintaining pure MIMOSA-based solutions too expensive for any organization.

IV. The MANTIS Interoperability Framework

A. Interoperability Perspective

Interoperability represents a perspective of the MANTIS-Architectural Reference Model (-ARM). A perspective defines a collection of activities, tactics, and guidelines that are used to ensure that a system exhibits a particular set of related quality properties that require consideration across a number of the system's architectural views [19]. Therefore, interoperability perspective is something orthogonal to the several views defined within the MANTIS-ARM. Fulfilling qualitative requirements through the architecting process inevitably leads to design challenges, related design decisions and design choices. Since there is usually more than one solution to each of the design challenges, the MANTIS ARM cannot guarantee interoperability between any two concrete architectures, even if they have been derived from the same requirement set. Nevertheless, the MANTIS ARM is an important tool in helping to achieve interoperability between MANTIS-compliant systems and within the MANTIS concrete platform itself by relying on the MANTIS-IF. With this in mind, the compatibility levels presented in Table 1 are considered within the envisioned interoperability framework. These levels are classified according to specific device/CPS features, namely: i) device communication part; and ii) device application part.

B. Specification of the Interoperability Framework and Research Method

The MANTIS-IF has been created around two fundamentals levels that are in line with the overall vision of the project, namely:

- Edge level: focuses on a set of physical entities belonging to the same local system. At this level, the data extracted from physical entities is used to model and analyse the behaviour of the local system. The edge level also includes a sublevel that is the component level where physical entities are analysed singularly.
- Cloud level: focuses on the information exchange and data integration in the cyberspace. At this level the data coming from the edge level is organized in order to be processed to analyse the overall system behaviour.

Within these two levels several interoperability issues and/or questions arose, and research solutions have been provided to address the identified problems. In particular, the interoperability framework has been designed to: i) identify a model that describes CPS an its relations with the other actors of a CPS-populated system; ii) identify the main interoperability issues for common architectural patterns (e.g. cloud-based and/or edge-based software systems); iii) enable the integration of distinct types of physical entities within MANTIS; iv) structure models and to design methodologies for systemizing interoperability in CPS-populated systems.

The design of the MANTIS-IF follows a well-structured and defined approach that can be divided into two main phases (see Fig. 2).

Table 1 Device Application and Communication Features adapted from [20]

Feature	Description	Interoperability Level
Device Communication part		
Communication Protocol	This feature consists of all protocols of layer 1 to 7 of the OSI reference model, i.e. from the physical medium access to the application layer protocol.	Physical
Communication Interface	This feature consists of the communication service definition of application layer including the services and the service parameters. Additional mapping mechanisms can be necessary. The dynamic performance of the communication system is part of this feature.	
Data Access	This feature consists of the object operation definition or the access parameter attributes of the block data input, data output and parameters	Syntactic
Device Application Part		
Data Types	The data type of the object attributes or block data input, data output or parameter defines this feature.	
Data Semantics	This feature consists of the characteristic features (parameter attributes) of the application data this can be data name, data descriptions, the data range, Substitute value of the data, default value, persistence of the data after power loss and deployment.	Semantic
Application Functionality	This feature consists of specifying the dependencies and consistency rules within the Functional Elements. This is done in the data description part or in a separate behaviour section.	Organizational Functional
Dynamic Behaviour	This feature consists of time constraints that influence the data or the general device behaviour. For example the update rate of a process value can influence block algorithms.	

The phase 1 is about requirements analysis and is intended to characterize the concrete system with the objective of identifying interoperability needs and location. During this phase, the following steps are performed:

i. Use Case Analysis: characterization of the use case concrete architecture in which the MANTIS platform will be integrated;
ii. Cloud Interoperability needs: identification of the interoperability issues at cloud level;
iii. Edge Interoperability needs: identification of the interoperability issues at edge level;
iv. Component Interoperability needs: identification of the interoperability issues at component level; and
v. Base technology: identification of the base technologies.

The phase 2 is about interoperability models' application and is intended to apply the provided interoperability specifications to respond to the interoperability requirements gathered during phase 1. During this phase, the following steps are performed:

i. New Tools and technology: to identify tools and technologies that could potentially help/facilitate the integration of the MANTIS platform within the pilot ecosystem;
ii. Component Interoperability model: to apply the provided models at the component level to enable integration between physical entities and cyber entities to create CPS;
iii. Edge Interoperability model: to apply the provided models at the edge level, i.e. between several components within the same local network
iv. Platform Interoperability model: to apply the provided models at the cloud level, i.e. integration between cloud digital artefacts that are responsible to process the data provided by CPS;
v. Specification and guidelines for interoperability: the results of the previous steps have been used to compile a set of specifications and guidelines and guidance for facilitating interoperability between the pilot ecosystems and the MANTIS platform.

By applying the proposed approach, a set of interoperability issues and/or questions have been identified that – in turn – triggered the development of the MANTIS interoperability framework. Inspired by previous works on the topic, the interoperability framework has been structured into three main parts:

- Conceptual integration: it is focused on concepts and their relationships, models and meta-models. It provides the modelling foundation for systemizing the relevant interoperability aspects for the specific application domain;
- Application integration: it is focused on methodologies, guidance and patterns to support the design and development of their own MANTIS concrete instantiations; and
- Technical integration: it is focused on technical aspects related to the networking (protocols, connectivity, etc.), hardware (CPU/memory power is already there, at low-cost and low-power consumption) and – more in general – to integration of heterogeneous data sources.

C. Conceptual Integration

The model for conceptual integration (see Fig. 3) has been created following a model-driven development approach to enable the design of interoperable and interconnected CPS-populated systems. It starts with the definition of a *domain model* that is aimed to capture the essence of the CPS while enabling the specification of the services and interfaces that the

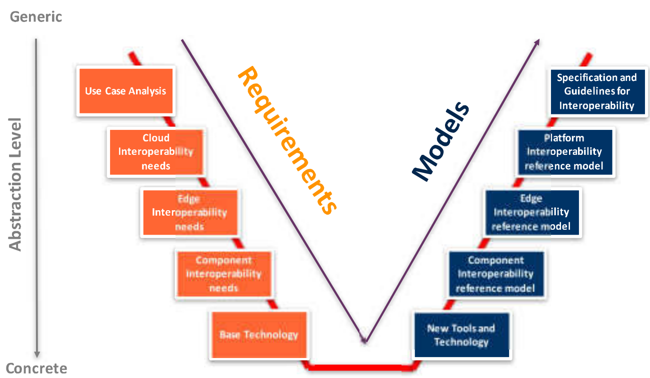

Fig. 2 MANTIS Interoperability proposed Approach

CPS must provide. The *domain model* is then complemented with the *semantic data representation and exchange model* and the *system interaction model*. The former is aimed to define and specify the structure of all the data and/or the information handled by CPS at the network level. The latter is aimed to define and specify the relevant events produced/consumed within the MANTIS platform, as well as, the distinct patterns for system interactions.

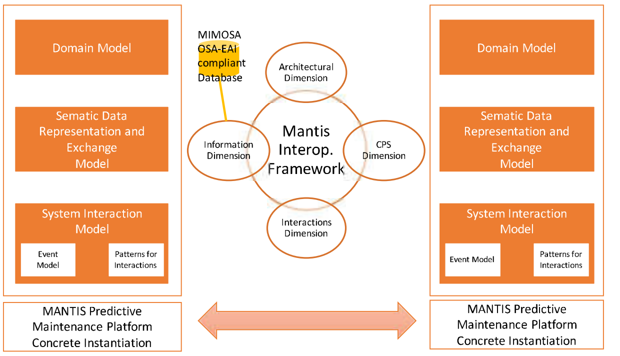

Fig. 3 Model for Conceptual Integration

The conceptual integration addresses specific interoperability issues – related with the design and the development of CPS-populated systems in line with the MANTIS reference architecture – within four main system dimensions, namely:

1. Architectural: is related with the specific/ concrete architectural pattern used to design the MANTIS platform. Interoperability issues are different in number, type and location if a cloud-based or an edge-based pattern is used and/or a façade, broker, mediator patterns are applied in those patterns;
2. CPS: is related to the design and development of a CPS, i.e. to provide guidance and guidelines on how to virtualize physical entities in terms of services/functionalities, especially for those that are low-tech;
3. Information: is related with the description of the data and the definition of the messages/structures exchanged, processed and stored within the MANTIS platform. The messages/structures exchanged are here also connected to a MIMOSA-compliant database that models the specific application context by using the MIMOSA OSA-EAI standard; and
4. Interaction: is related with the definition and the identification of the necessary message exchange patterns (MEPs), i.e. how messages/structures are exchanged within the MANTIS platform.

The previous dimensions can then be used to analyse CPS-based software system from the interoperability point of view to help the design and deployment of MANTIS interoperable concrete platforms while identifying the critical interoperability issues and major challenges.

D. Application Integration

The model for application integration (see Fig. 4) has been developed to capture and show how the provided interoperability models can be related to a concrete MANTIS platform instantiation without specifying and/or establishing any technology. In particular the model for application integration shows the relation between the model for conceptual integration and the concrete technical environment used for developing maintenance platforms compliant with the MANTIS-ARM for the sake of interoperability.

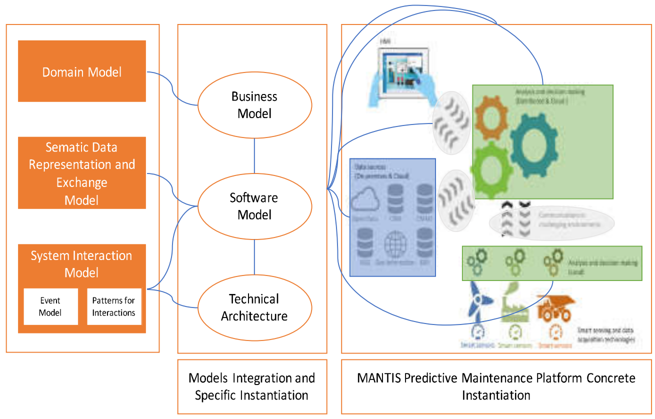

Fig. 4 Model for Application Integration

The *business model* describes the specific domain for the software solution that need to be implemented. It is aimed to provide a solid foundation for the design and implementation of a MANTIS interoperable platform, i.e. to relate the CPS domain model to the specific application domain. The *software model* represents the instantiation of the *semantic data representation and exchange model* and *system interaction model* in the specific domain derived from the *business model*. Therefore, in the *software model* all the necessary models of the conceptual integration are included. Finally, the *technical architecture* represents and describes the concrete environment, infrastructure and related technologies for supporting the platform/application. In particular, in the context of MANTIS project, the Arrowhead framework have been chosen as the reference technology for providing the necessary infrastructure while acting as a system integrator solving the physical and the syntactic (partially) interoperability level.

As shown in Fig. 4, the *business model*, *software model* and *technical architecture* are then used for developing MANTIS concrete platforms by addressing the specific architectural pattern, the data sources (in blue in Fig. 4), the structure and the flow of data in the analysis and decision making core (in green in Fig. 4), and the description and definition of the necessary communication channels and patterns (in grey in Fig. 4).

E. Technical Integration

The technical framework of the MANTIS-IF describes the MANTIS platform (see Fig. 5) from the interoperability perspective. The architecture is centered on a set of CPSs, core services and related execution engine, processes, data analytics processors, tools and applications that are aimed to support maintenance activities in CPS-populated systems.

The model is represented by a 4-tier model that cover all the necessary issues and aspects that developers need to consider whenever they want to implement MANTIS-compliant systems, i.e. data representation and exchange, system interactions (event models and patterns for interaction), data transformation and translation and services and functionalities definition, as well as, physical entities virtualization (domain model). The data and

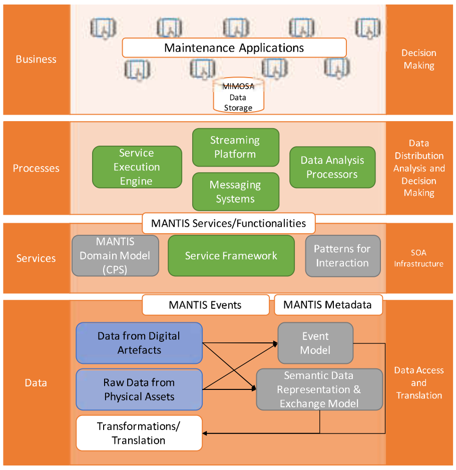

Fig. 5 Model for Technical integration

services tiers are intended to be coupled and supported by a SOA-based communication infrastructure that, in turn, provides the necessary mechanisms for discovering, composing and orchestrating the services. In particular the service framework (at the service tier), and the whole process tier represent the real technology where the interoperability models and specifications are instantiated. A central part of the framework is the MIMOSA data storage that acts as a facilitator for the design and implementation of maintenance applications within the business tier. To empower the use of the MIMOSA data storage, i.e. to permit the storage of the MANTIS events and related metadata, translators and transformations are created.

V. Conclusions and Future Developments

CPS-populated systems can potentially have a tremendous impact in all the application domain. In the industrial context, they can support the optimization of all the activities associated with the production process as well as implement new customer-centric business models. However, this is true only if sophisticated and efficient information models and exchange mechanisms are in place to guarantee that all the actors of a CPS-populated system are capable to exchange and use the information exchanged. Nowadays, the interoperability problem is far to be solved and the dissemination and proliferation of new technologies and devices is adding more and more complexity. One way to address this problem is to standardize and homogenize the way data are represented and structured to cope with the problem of integrating data from multiple vendor-based systems for the sake of data and information exchange.

In this paper, the MANTIS-IF has been described. It is based on the notion that open standards for exchanging maintenance data about assets and resources can lead to a raft of possibilities for implementing advanced maintenance paradigms and strategies in enterprises. However, open standards (like MIMOSA) are not fully mature and require the design and development of meta-models to facilitate the implementation of interoperable solutions.

Future developments include the refinement of the proposed framework and the design of a methodology on how to apply the framework in real application scenarios.

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