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2nd International
Electronic Conference on
Sensors and Applications
15–30 November 2015

www.mdpi.com/journal/sensors

Conference Proceedings Paper – Sensors and Applications

Smart Systems and Cyber Physical Systems paradigms in an IoT and Industry/ie4.0 context

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Published: 11 November 2015

Abstract: This paper aims at helping to bring about a better understanding of the relationship between Cyber-Physical Systems (CPS) and Smart Systems and Smart System Integration paradigms, analysing the coexistence, overlap and specific differences in terms of domains of application of the two concepts, in an IoT and Industry/ie4.0 context. For that purpose, in this paper different 'views' are presented that correspond to different modalities or classes of applications, and examples are given of their application to support the analysis. A first look is taken at definitions. A definition for Smart Systems in common use emphasises externally visible functionality and the heterogeneous components required to implement Smart Systems, in particular direct or indirect sensing and actuating functions and respective interfacing. The common CPS definition emphasises collaboration and communication between the CPS nodes, treating sensing, actuation and external communications technologies more as an abstract given. The analysis presented has been proposed to EPoSS in order to improve the perception of these paradigms within the EPoSS (European technology Platform on Smart Systems integration) and ECSEL (Electronic Components and Systems for European Leadership) communities, and outside in the FoF (Factory of Future) and Industry/ie4.0 communities.

Keywords: Cyber-Physical Systems (CPS); Smart Systems Integration (SSI); Internet of Things (IoT); Industrie/y4.0;

1. Introduction

Smart Systems promise to bring a wealth in capabilities and functionalities in every sector in which they can be introduced and utilised. It is their intrinsic nature and scope to provide innovative solutions in ever more application fields, further increasing their pervasiveness in all possible market sectors (Manufacturing / Factory Automation, Health & Beyond, Aerospace & Defence, Clothing & Textiles, Transport & Mobility, Security & Safety, Energy, Environment, Communications, Home & Entertainment, Agriculture, Fisheries, Food & Beverages, etc.), further acquiring a fundamental role in societal challenges, as defined in Horizon 2020 programs.

Smart Systems and Manufacturing can be related to two categories of primary importance:

- Smart System Integrators,
- Developers and Smart System Users.

The acronym SSI, Smart System Integration, refers to the principles and techniques that are used in development and implementation of (Integrated) Smart Systems (I-SS or SSI) and Cyber Physical Systems (CPS).

Smart System manufacturers, system integrators, developers and researchers applying new technologies, provide new capabilities and functionalities to the resulting products (finished systems or subsystems).

Smart Systems and CPS look for the application of Key Enabling Technologies or KETs (Micro & Nano Electronics, Nanotechnologies, Biotechnologies, Photonics, Advance Materials, and Advance Manufacturing) and adopt the advanced manufacturing for products and other developments.

They, functionally, take the role of solution providers and enablers of methodologies strictly related to technological base principles, capitalising on value from the KETs as well as from a more pervasive introduction of ICT and Cyber approach.

The development and implementation of Smart System solutions constitutes the second relevant category. Inside the manufacturing sector Smart Systems are becoming a set of powerful tools for the implementation and divulgation of new paradigms in production, planning, maintenance and services.

Smart Systems in manufacturing promise to carry out local optimisation supported by local knowledge bases, ranging from the examination of raw materials and parts - suggesting subsequent machine settings to compensate for variations, allowing smart maintenance of the production plant - all the way through to optimising manufacturing parameters based upon measured end-product performance.

2. Analysis of the SSI and CPS paradigms

Definitions for Smart Systems in common use emphasise externally visible functionality and the heterogeneous components required to implement Smart Systems, in particular direct or indirect sensing and actuating functions and respective interfacing. We summarise the attributed of these definitions in the following definition:

(Integrated) Smart Systems (I-SS or SSI) are defined as (multi-) sensor and actuator based devices that are capable of describing, diagnosing and qualifying given complex situations, to make predictions, to cast decisions and to take actions. They are networked, autonomous and as small as possible.

Common CPS definitions emphasise collaboration and communication between the CPS nodes, treating sensing, actuation and external communications technologies more as an abstract given. We following definition (from ECSEL, Electronic Components and Systems for European Leadership):

Cyber-Physical Systems (CPS) are the next generation embedded intelligent ICT systems that are interconnected, interdependent, collaborative, autonomous and provide computing and communication, monitoring/control of physical components/processes in various applications incl. safety critical.

Further references to Smart Systems and CPS definitions are given under References and Notes.

The analysis here observes that SSI and CPS are largely overlapping paradigms describing what is considered to be essentially the same phenomenon; however, differentiated by the fact that each includes an area that is not, or not so well covered by the other.

To illustrate this, our analysis makes use of 3 'views' starting from the well asserted model for Smart Systems, as given in Figure 1, where sensing and actuation, by means of any possible useful technology, are a fundamental part of the system that is defined in its capability to manage data acquisition and process data into information and actions.

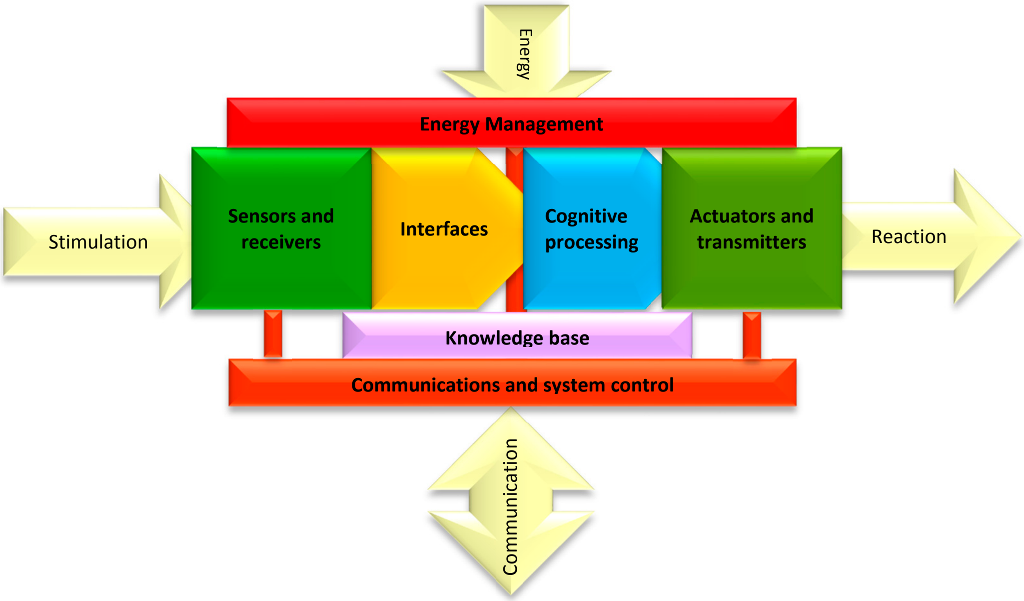

Figure 1. Smart System Main Blocks, Reference Scheme.

The energy management block can also include energy harvesting from several sources. This feature is increasingly in demand by the increasingly widespread use of off-grid applications, such as distributed sensor networking, in which extension of the battery life is a strongly felt need and in which 'battery-less' applications are ever more desirable.

From the application side, the approach followed addresses the definition of architecture and the specification for the specific Smart System design. This is reflected in the same general approach for Smart Systems by different 'views' in which the different main blocks are based on application requirements fixing common characteristics, especially on the grade of interoperability with other systems, for similar application solutions.

We can define three typologies on the basis of their interaction capability that can be defined as

- A stand-alone solution,
- A solution as part of an overall well defined distributed system, and
- A solution as part of a system of systems where there isn't a unique, fixed reference system.

We then introduces three 'views':

- Edge view;
- (Distributed) System view;
- System of Systems or Distributed Autonomous Dynamic decisions (DAD) view (also referred to as Decisions Autonomous, Distributed and Dynamic (DADDY) view).

The first type of application of Smart Systems is to consider an 'Edge view', in which a well-defined boundary between 'the system' and the outside is recognised as defined by the application, as shown in, Figure 2.

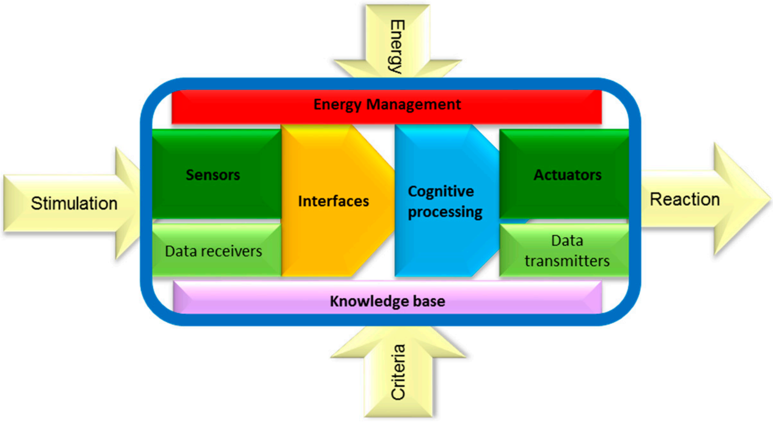

Figure 2. Smart System 'Edge View'.

A typical example shown in Figure 3 is that of a cardiac stimulator that provides specific functions on the basis of its own context awareness, without or with limited interaction with other electronic systems. In this description, generally, the Smart System represents the (core of the) whole system.

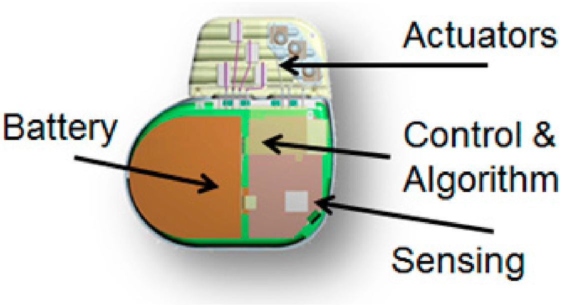

Figure 3. 'Edge View' Example: Cardiac Stimulator.

Another view is that of the '(Distributed) System view' that emphasizes the externally visible functionality for a more or less complex system, in which an interdisciplinary knowledge is applied by means of heterogeneous integration, with the aim to provide multi-functional solutions, integrating sensing, actuating, processing, power management, control, communication, as shown in Figure 4:

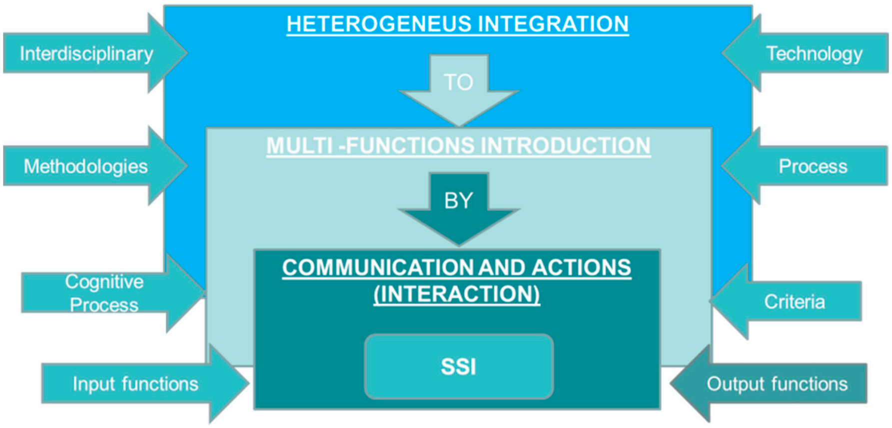

Figure 4. Smart System 'System View'.

In this view, Smart Systems ensure specific functions on the basis of their specific integration of heterogeneous technologies, and this will be delegated by and under control of a main system by means of specific communications.

This is the case, for example, for each Smart Systems integrated in a vehicle, in which they have each specific functions, such as in airbag, EPS, ABS, and all powertrain functions, for example for an Electric Vehicle (EV), as shown in Figure 5; or, for the camera module for a PCs, laptops and mobile phones, and its integral parts such as an Optical Image System (OIS) for image stabilization, as shown in Figure 6.

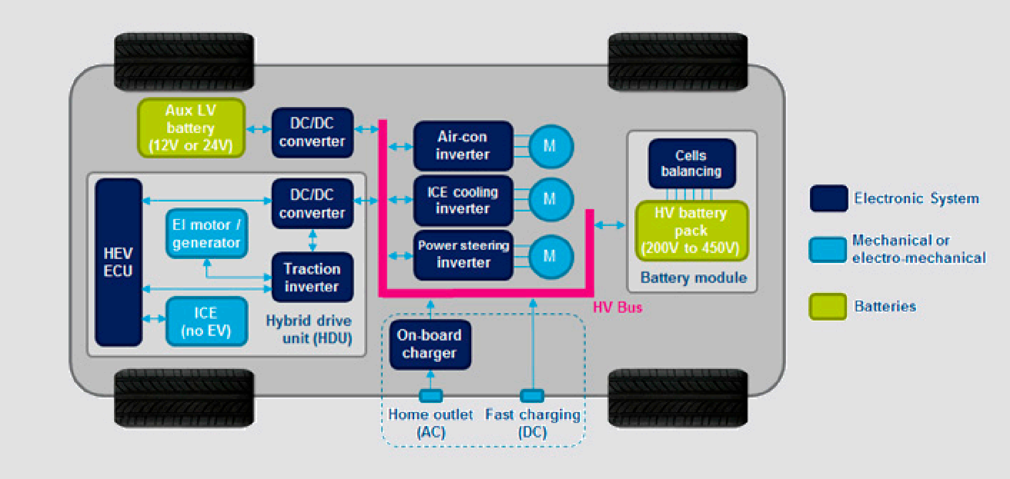

Figure 5. Smart System 'System View' Example: EV Sub-systems.

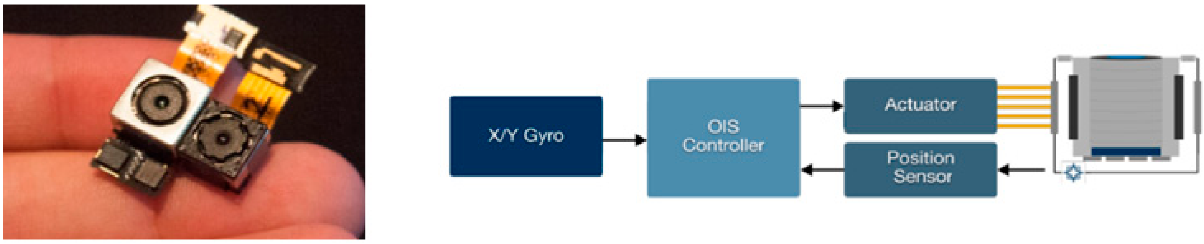

Figure 6. Smart System 'System View' Examples: Camera Module and its OIS System.

In these System solutions, the effort for 'integration' is mainly focused on feasibility and reliability of specific 'subsidiary' functions at 'global' level, while the interaction with the overall system is limited to ensuring these functionalities.

The last representation, System of Systems, is linked to the recent evolution in communications, protocols stacks and devices that, on the wave of the large diffusion of PCs, laptops and smartphones, has made available affordable sophisticated communication methodologies and tools characterized by high data throughput and more complex handshakes, that in return require an increase in processing capabilities to be fully adopted in Smart Systems.

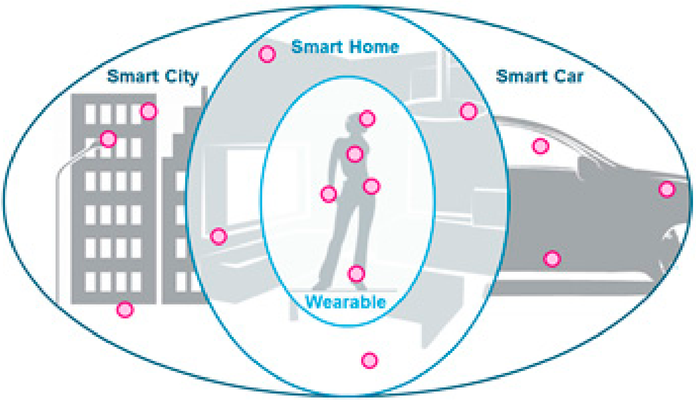

Figure 7. Smart System Node Possible Interactions

Figure 7 represents the possible interactions of Smart Systems (red circle) becoming 'Smart Nodes'. This has an impact on the architectural definition and design of the Smart Systems that will need to be able to provide different ways of communication, generally for short range interaction with other devices, and for a vertical integration and contribution to the overall system domain, as shown in Figure 8.

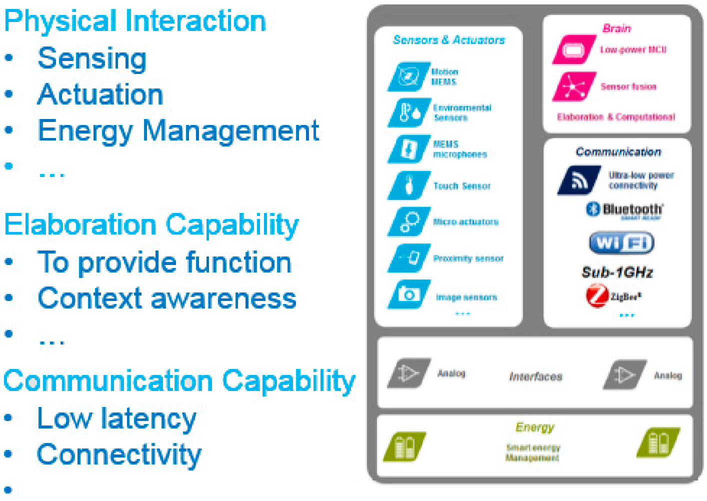

Figure 8. Smart Node Typical Characteristics.

The communication path for the latter is implemented through a collection of heterogeneous communications layers/domains, coordinated and organised in the form of a unique environment with seamless continuity, in which connected things/objects and devices perform common interactions by means of a cooperative provision of digital information and data manipulation, as shown in Figure 9, showing both Hardware (HW) and Software (SW) aspects.

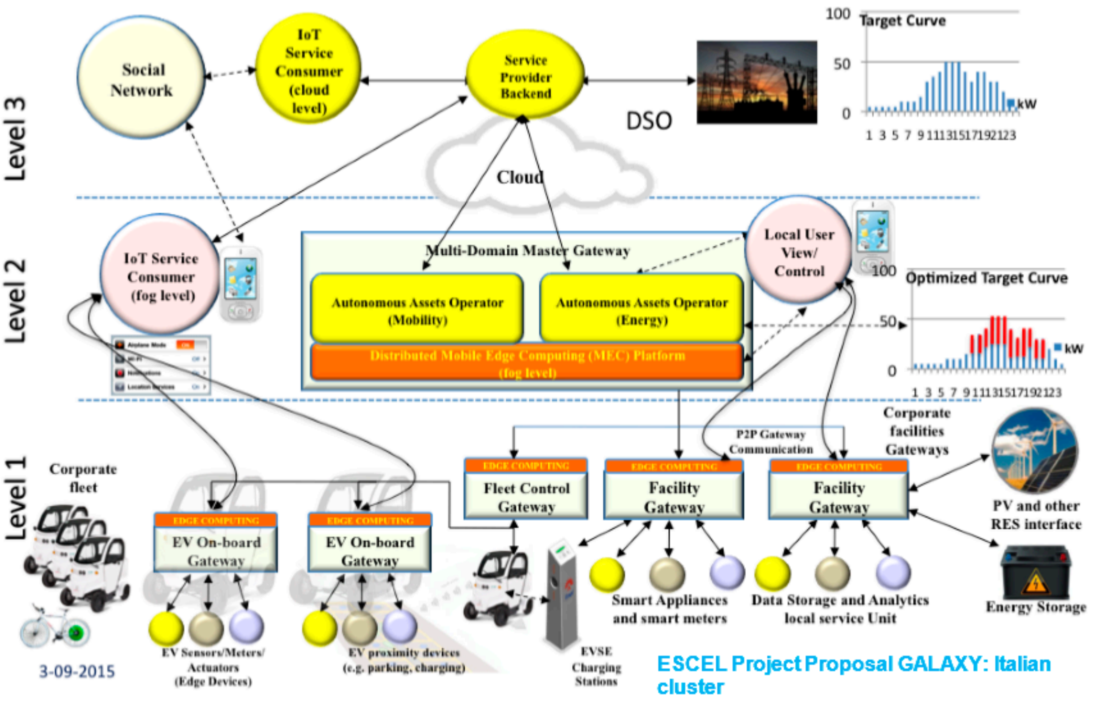

Figure 9. Example of High-Level Architecture.

On the basis of the own capability to participate to this common interaction, Smart Systems become part of an IoT architecture as physical edge and objects of this vertical integration; Figure 10 shows an example.

Smart Systems expand in an IoT context with specific, aimed and clear functions, as well as sensing and actuation, deploying the interface between the real physical and its cyber-augmented world by means of accessible services on networks. Figure 11 represents several examples in different IoT application domains.

A vision for a smart node, able to support and to be integrated in this kind of high level architecture has been defined as 'System of Systems view' or 'DAD view': Distributed, Autonomous and Dynamic decision taking clusters.

This includes potentially large clusters and 'cloud' interactions, with local decision taking according to a Distributed, Autonomous and Dynamic paradigm, characterized by a low latency on communications and large connectivity, and adequate processing capability of the local context awareness.

Actually, due to the latency and limited data throughput on a network, the awareness of the context, as shown in Figure 11, especially real time or just in time more than near in time, cannot be obtained by Big Data management and extensive Software (SW) tasks, so it is required to turn to edge/local computational capabilities increasing the 'low level' or first line processing and interpretation.

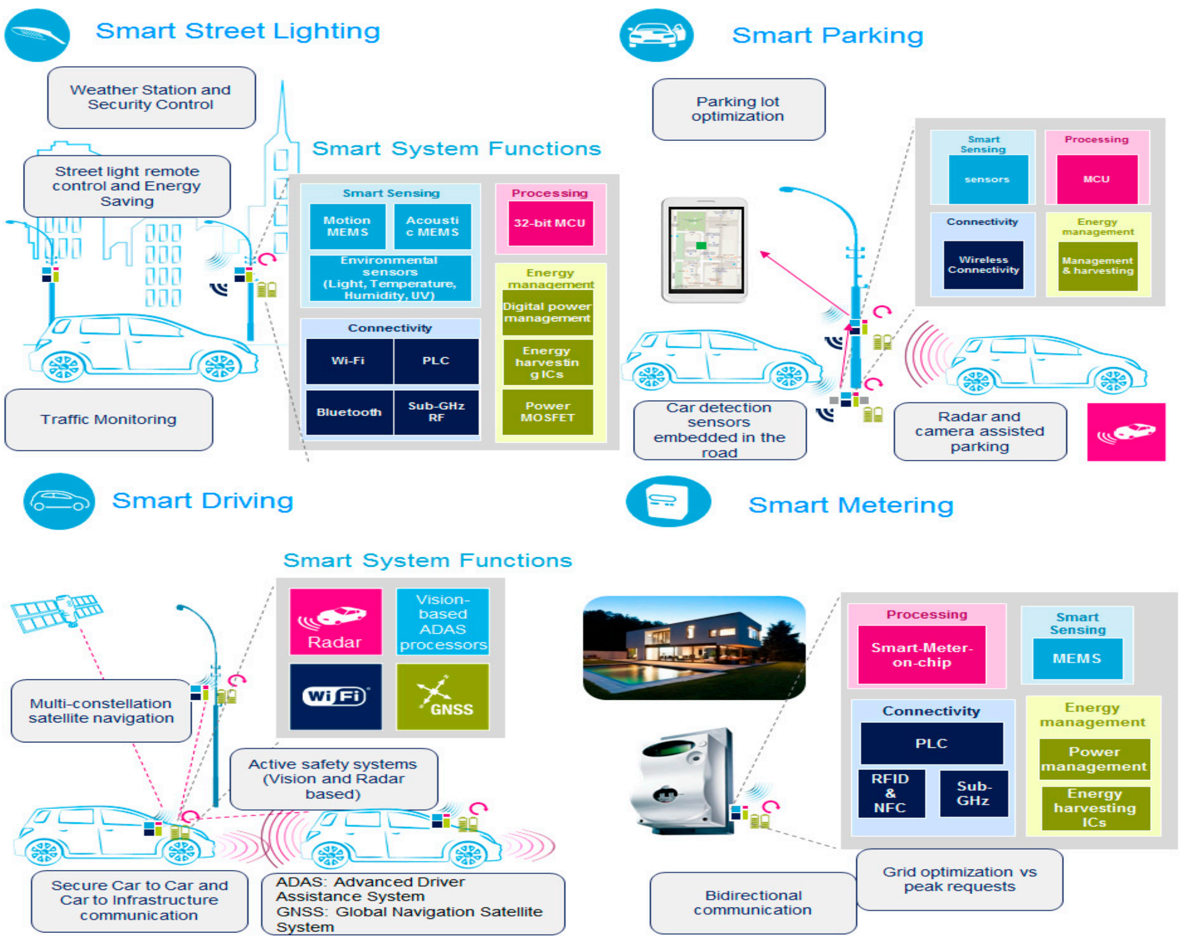

Figure 10. Smart System Utilization in IoT Application Domains.

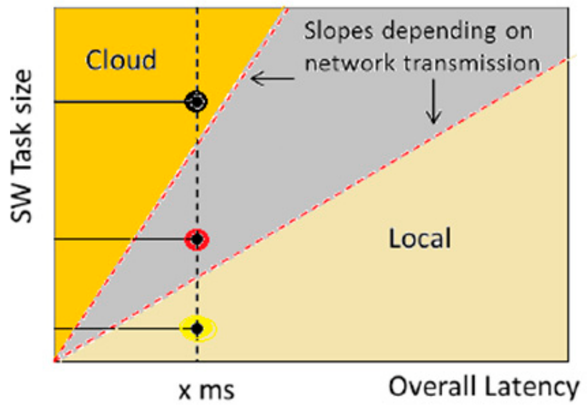

Figure 11. Constraints on Context Awareness Displacements.

As shown in Figure 11, we can define 3 areas in which, on the basis of communication capabilities and the time to respond, the ‘action’ has to be the responsibility of the Cloud (high level software task and large amount of data to manage) or of the local devices. The low cost of microprocessors and memories allows the introduction at edge level of ever more processing and interpretation capability, exploiting the adoption of sophisticated communication protocols, moving the handshaking among devices into an applications management under M2M paradigms; an example of a possible M2M implementation of a Mobile Edge Computing (MEC) Server, is presented in Figure 12.

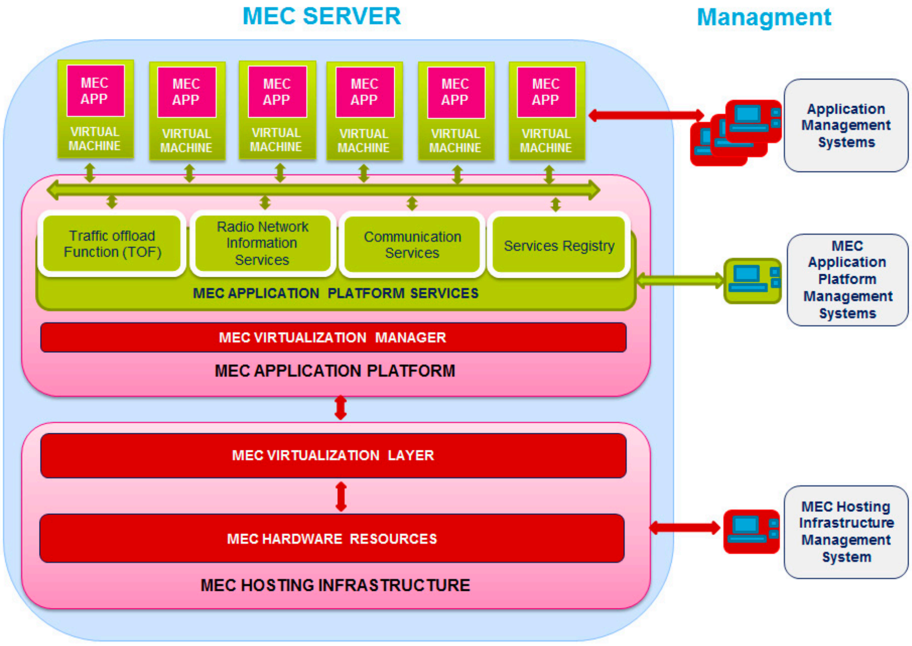

Figure 12. Example of M2M Implementation of a MEC server.

The analysis of the three views leads to a relatively simple set of conclusions, giving guidance on when both paradigms are to be considered equivalent, and when one paradigm is better suited than the other when describing an application scenario.

3. Discussion

We are facing an imminent change in the factory and manufacturing domain that promises to be the start of a remarkable evolution of the entire manufacturing sector by utilizing means the exploitation of the high potential offered by new technological and smart solutions in synergy with an advanced integration of ICT solutions. This change also seems to be able to revert the current trend to move production into countries with low labour (and other societal) costs.

Generally, as Figure 13 shows, a production line involves activities and services that are not restricted to the effective production of goods, but that are required for the process flow and management.

Major essential and ancillary activities on the production line itself are the logistics of materials/parts, the energy supply / consumption, the management of waste, and the planning process that orchestrates the elements of the process, just-in-time provisions with suppliers, and the delivery schedules to customers.

The introduction in the production plant process of new architectural instruments allowing, for example, virtual engineering, new MES (Manufacturing Execution Systems - to optimize the whole production activity from order launch to the completion of the products), new distributed production, and a modular approach, should provide an evolutionary real enhancement of manufacturing process control.

These evolutionary changes will lead to a new revolutionary manner of production with the flexibility to allow goods customization and with a better management of the inside and outside factory resources, whose coordination becomes an active part of the production process.

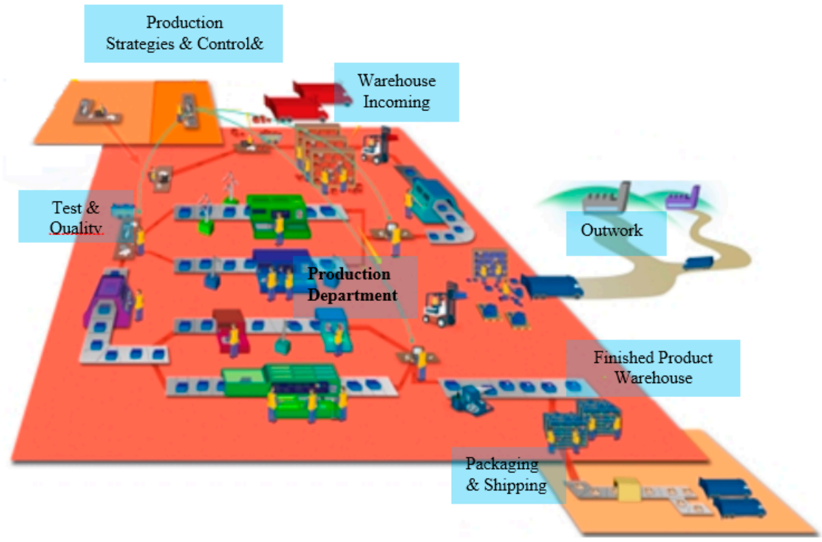

Figure 13. Example of Possible Layering in Process Control.

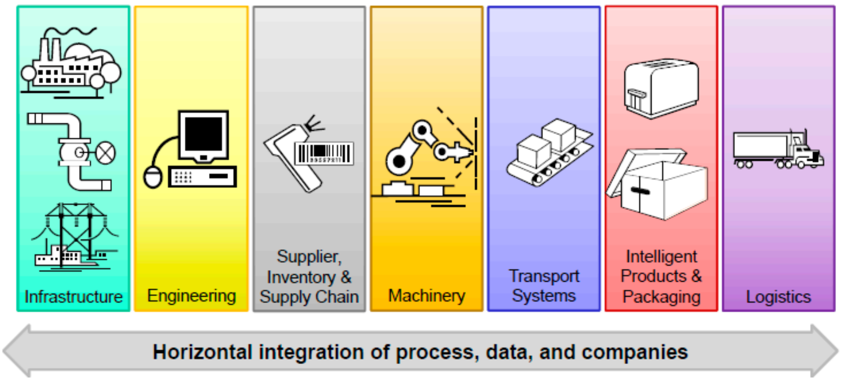

Figure 14. Horizontal Integration Across Multiple Value Chains.

Characteristics of this evolution are both a large horizontal integration, as shown in Figure 14, across multiple value chains, of process, data, and companies, and a strong interaction by means of a vertical integration, as shown in Figure 15, at Corporate level (Business Processes /Enterprise Resource Planning), Plant Operational level (Manufacturing Execution Systems, and material, quality management, KPI determination), Process management level, control level, field level (sensor and actuators, shop-floor).

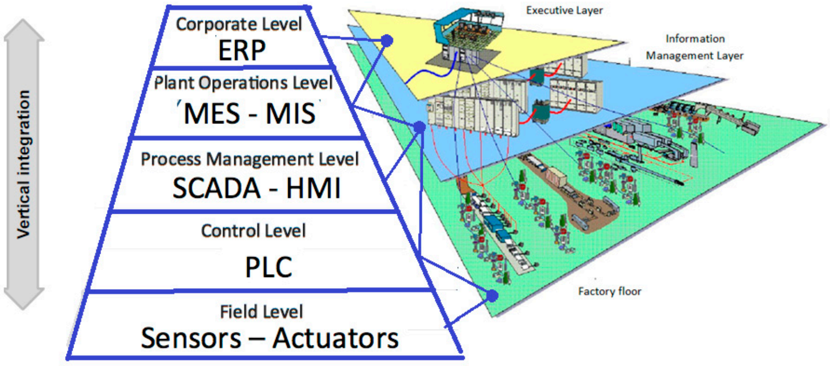

Figure 15. Industry Vertical Integration.

Implementing a more dynamic value chain, from customer and retailers down to production planning and logistic, is the vision of Industry/ie4.0.

Industry/ie4.0 is designed to improve the ability to combine and overlay the real world on the virtual world in the form of Cyber-physical Systems (CPS) defining a new production approach.

In this new approach, the smart machineries, the warehousing systems, the production facilities, the business processes, in brief, every part of the manufacturing ecosystem, will be capable of autonomously exchanging information, triggering actions and controlling each other autonomously and independently.

The Introduction of Smart Systems in the third view in manufacturing, ensures the required evolution of the factory and brings inside the production line with the capability of Smart Systems management of sensing and actuation and, at the same time, manipulation information.

This will allow monitoring of the actual production status, allowing changes in parameters to react better to variations, and to take advantage of maintenance plans by a pervasive ICT with distributed awareness and smartness in the equipment that becomes ever more able to collect and cluster information.

For example, the massive introduction of Smart Systems into manufacturing equipment allows to catch the benefits from a distributed intelligence and smartness promising more flexibility for product changes, customisation and optimisation, increasing the overall throughput and line quality and controlling of the process' micro-environment, and providing a more continuous information flow.

On the production floor, advanced ICT architectures, in synergy with a large introduction of Smart Systems, will offer efficient functional 'layers' able to provide and sustain the required innovation for this '(r)evolutionary' industrial production.

These solutions will be also able to overcome the typical issues that appear when updating in the production line is required to satisfy constraints and requirements, and that provide an improvement in flexibility, sustainability and in time to market.

Smart Systems and ICT introduction will ensure the needed flexibility to implement changes in process control, accomplishing needed changes inside the organization of work/production, such as:

- Moving/splitting the production sections into coordinated sets of working isles/modules to favour an increased flexibility of the production (improving customisation);
- Reducing minimum quantity for orders and increasing timeliness in response (also reducing stock);
- Moving from a production model linked to the concept of 'proximity and territorial community', into a 'simultaneous' model, where a worldwide networked manufacturing is part of the production strategy;
- Carrying out local optimisation supported by local knowledge bases, such as the examination of raw materials and parts and suggesting subsequent machine settings to compensate for variations;
- Moving the test and inspection from off-line laboratory instruments into procedures for in-line and on-line testing and inspection;
- Optimising machine parameters based on measured product performance.

4. Conclusions and Outlook

Any improvement in possible interactions and/or on communication capabilities gives further opportunities for Smart System exploitation, and makes feasible new functionalities on the basis of the obtained grade of interconnectivity.

This means that, if we would form a vision on the achievable innovation in relation with the introduction of Smart Systems in manufacturing and in factory automation process, we would observe not only the improvements allowed by exploitation of technology and by advanced manufacturing, but also the developments in:

- Communications infrastructure,
- Standardisation of protocols able to ensure the data ownership management, security and privacy in compliance with requirements of industry and industrial production,
- improved workers' skills, to allow the adoption of new design and modelling tools able to better describe and deal with the growing request of integration of ever more heterogeneous systems/domains for Smart applications,
- Possible evolution of the regulatory framework to support the implementation and to ensure that new achievable innovations comply with the new and existing legislations.

A long-term vision would be looking at the future interactions in different domains and environments, allowing new kinds of solutions and applications.

The interest to this kind of approach is confirmed by several initiatives related to the Factories of the Future, at national and regional and European level, as such:

- Industry/ie4.0 (originating from Germany)
- High Value Manufacturing (UK, Catapult, the MTC)
- Fabbrica Intelligente (Italy, in particular Lombardia and Piedmond)
- Basque and Catalane initiatives (Spain)
- Smart Industry (Netherlands)
- Produtech (Portugal)
- Usine du Future (France)
- Made Different, Flanders Make (Belgium)

At global level, for exploitation and synergy between the SSI, CPS and IoT, and the industry paradigms, we can refer to:

- 'Re-industrialization', 'Smart Manufacturing Leadership Coalition' (USA)
- 'Industrial Internet' (GE)
- 'Connected Enterprise' (Rockwell Automation)
- 'Industrial Intelligence' (Japan)
- 'Manufacturing Intelligence 2025' (China)
- 'Manufacturing Innovation 2.0' (Korea)

Conflicts of Interest

The authors declare no conflict of interest.

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- The term CPS is also widely used in the USA. There has been a series of significant research initiatives and activities in CPS over the past decade, including several US federally funded workshops. Information may be found at the CPS Virtual Organization website. (http://cps-vo.org/).
- It should be noted that the importance of CPS was clearly recognized in the 2007 report of the USA President’s Council of Advisors on Science and Technology (PCAST) ‘*Leadership Under*

Challenge: Information Technology R&D in a Competitive World', PCAST report, 2007. (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-07-nitrd-review.pdf). The report ranked research in CPS as number one funding priority and it did pave the way for significant research funding.

- The importance of CPS was reaffirmed in the 2010 PCAST report '*Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*", PCAST Report, December 2010 (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf) and in subsequent reports. See for example the 2013 PCAST report '*Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*', PCAST Report, January 2013 (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd2013.pdf).
- See also 'Winning the Future with Science and Technology for 21st Century Smart Systems' by the Office of Science and Technology Policy-White House (OSTP) found at http://cps-vo.org/node/6110.
- Additional information may also be found in the Impact of Control Technology report; see http://ieeecss.org/general/impact-control-technology at the website of the IEEE Control Systems Society.