Chapter 11
Trends and Challenges for Cloud-based Industrial Cyber-Physical Systems

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Abstract The domain of industrial systems is increasingly changing by adopting emerging Internet based concepts, technologies, tools and methodologies. The rapid advances in computational power coupled with the benefits of the Cloud and its services, has the potential to give rise to a new generation of service-based industrial systems whose functionalities reside on-device and in-Cloud. Their realisation brings new opportunities, as well as additional challenges. The latter need to be adequately addressed if the vision of future Cloud-based industrial Cyber-Physical System infrastructures is to become a reality and be productively used.

11.1 Vision and Trends

We move towards an infrastructure that increasingly depends on monitoring of the real world, timely evaluation of data acquired and timely applicability of management (control), several new challenges arise. Future factories are expected to be complex System of Systems (SoS) that will empower a new generation of today hardly realizable, or too costly to do so, applications and services [6]. New sophisticated enterprise-wide monitoring and control approaches will be possible due to the prevalence of Cyber-Physical Systems (CPS) [1, 10]. The different systems will be part of a larger ecosystem, where components can be dynamically added or removed and dynamic discovery enables the on-demand information combination and collab-

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oration [3, 17, 4]. All these are expected to empower the transformation to a digital, adaptive, networked and knowledge-based industry as envisioned for Europe [5, 7].

The emerging approach in industrial environments is to create system intelligence by a large population of intelligent, small, networked, embedded devices at a high level of granularity, as opposed to the traditional approach of focusing intelligence on a few large and monolithic applications [3, 4]. This increased granularity of intelligence distributed among loosely coupled intelligent physical objects facilitates the adaptability and reconfigurability of the system, allowing it to meet business demands not foreseen at the time of design and providing real business benefits [13, 16].

Some of the key trends [10] with significant impact on the industrial systems include:

- *Information Driven Interaction*: Future integration will not be based on the data that can be delivered, but rather on the services and intelligence that each device can deliver to an infrastructure. The Service-Oriented Architecture (SOA) paradigm [2] enables the abstraction from the actual underlying hardware and communication-driven interaction and the focus on the information available via services.
- *Distributed Business Processes*: In large scale sophisticated infrastructures, business processes can be distributed in-network e.g. in the Cloud and on the device. Thus processing of information and local decisions can be done where it makes sense and close at the point of action.
- *Cooperating Objects*: Highly sophisticated networked devices are able to carry out a variety of tasks not in a standalone mode as usually done today, but taking into full account dynamic and context specific information. These "objects" will be able to cooperate, share information, act as part of communities and generally be active elements of a more complex system [15].
- *Cloud Computing and virtualisation*: virtualisation addresses many enterprise needs for scalability, more efficient use of resources, and lower Total Cost of Ownership (TCO) just to name a few. Cloud Computing is emerging powered by the widespread adoption of virtualisation, Service-Oriented Architecture and utility computing. IT services are accessed over the Internet and local tools and applications (usually via a web browser) offer the feeling as if they were installed locally. However the important paradigm change is that the data is computed in the network but not in a priori known places. Typically physical infrastructure may not be owned and various business models exist that consider access oriented payment for usage.
- *Multi-core systems and GPU computing*: Since 2005 we have seen the rapid prevalence of multi-core systems that nowadays start to dominate everyday devices such as smartphones. The general trends are towards chips with tens or even hundreds of cores. Advanced features such as simultaneous multi-threading, memory-on-chip, etc. promise high performance and a new generation of parallel applications unseen before in embedded systems. Additionally in the last decade we have seen the emergence of GPU computing where computer graphic cards are taking advantage of their massive floating-point computational power to do

stream processing. For certain industrial applications this may mean a performance increase of several orders of magnitude when compared with a conventional CPU.

- *SOA-ready devices*: Networked embedded systems have become more powerful with respect to computing power, memory, and communication; therefore they are starting to be built with the goal to offer their functionality as one or more services for consumption by other devices or services. Due to these advances we are slowly witnessing a paradigm shift where devices can offer more advanced access to their functionality and even host and execute business intelligence, therefore effectively providing the building blocks for expansion of Service-Oriented Architecture concepts down to their layer. Web services are suitable and capable of running natively on embedded devices, providing an interoperability layer and easy coupling with other components in highly heterogeneous shop-floors [3, 13, 16, 4].

All of the aforementioned trends, heavily impact the next generation of industrial systems per se. The Cloud integration and interaction may be a game-changer in the CPS and will take a closer look at how CPS and Cloud fusion.

11.2 The fusion of Cloud and CPS

The first step in the infrastructure evolution was to empower the individual devices with Web services, and enable them to participate in a service-based infrastructure. This is achieved by enabling them to (i) expose their functionalities as services, and (ii) empower them to discover and call other (web) services to complement their own functionalities [3, 13, 16].

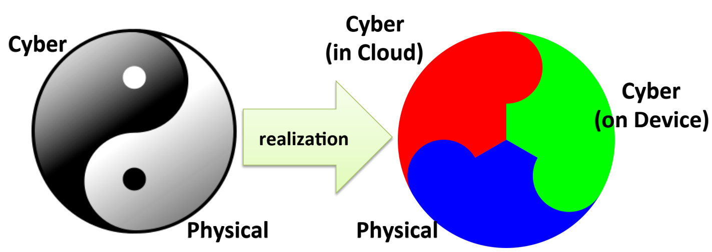

Fig. 11.1 Cloud-based Cyber-Physical Systems

The next step, is to take advantage of modern capabilities in software and hardware, such as the Cloud and the benefits it offers. As seen in Fig. 11.1, CPS have two key parts integrated in balance, the physical part for interacting with the physical environment (e.g. composed of sensors and actuator constellations), and the cyber part, which is the software part managing and enhancing the hardware capabilities of the CPS as well as its interaction with the cyber-world. The prevalence of the Cloud and its benefits [11], enables us to expand the cyber-part of the CPS and distribute it on-device and in-Cloud. As depicted in Fig. 11.1, CPS now may operate with three key parts constituting and forming their interaction in physical and virtual world.

The Cloud enabled CPS have profound implications for the design, development, and operation of CPS. Although the device-specific part, i.e. the cyber (on-device) and physical part are still expected to work closely together and provide the basic functionalities for the CPS, the in-Cloud cyber part may evolve independently. Due to its nature, the in-Cloud part will require connectivity of the CPS with the Cloud where added-value sophisticated capabilities may reside. On the contrary the on-device cyber-part may consider opportunistic connections to the Cloud, but in general should operate autonomously and in-sync with the physical part.

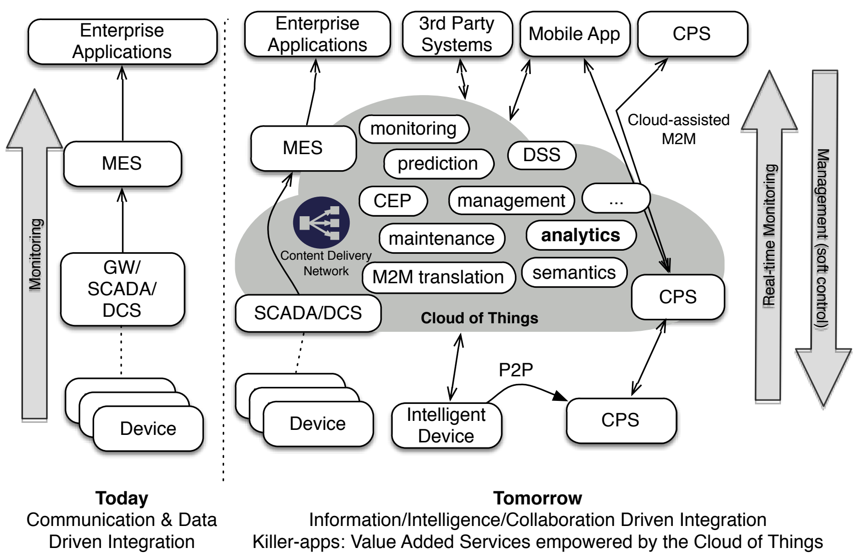

Fig. 11.2 Vision of Cloud-based SOA Industrial Systems

The nature of the functionalities as well as the degree of their dependence on external resources, computational power, operational scenarios, network connectivity etc. will be the key factor for hosting them on-device or in-Cloud. Nevertheless, typical considerations up to now about resource-constrained devices do not hold in general any more, as now the additional power needed from specific functionalities can be outsourced to the Cloud and hence the software/hardware needs for these functionalities is no longer required to be on the device itself [11]. The latter enables more flexibility for the design and operation of large industrial CPS infrastructures that act collaboratively, and may achieve more, by better utilizing their resources.

As an example of this era, we have to point out clearly, that the next generation SCADA/DCS systems may not have a physical nature but rather rely on federated actuators and sensors, while their main functionalities reside solely on the Cloud [10]. This implies that it might reside only on the cyber or "virtual" world, in the sense that it will comprise of multiple real world devices, on-device and in-network services and collaboration driven interactions, that will compose a distributed highly agile collaborative complex system of systems.

As shown in Fig. 11.2, the fusion of CPS and Cloud constitutes the "Cloud of Things" [11], which flourishes based on services offered to devices and systems, as well as depend on data from devices and intelligence built on the interaction among the physical and cyber (virtual) world. The benefit by utilizing the Cloud of Things is that additional capabilities potentially not available at resource constraint devices can now be fully utilized taking advantage of Cloud characteristics such as virtualisation, scalability, multi-tenancy, performance, lifecycle management etc. The manufacturer for instance can use such Cloud-based services in order to monitor the status of the deployed appliances, make software upgrades to the firmware of the devices, detect potential failures and notify the user, schedule proactive maintenance, get better insights on the usage of his appliance and enhance the product etc.

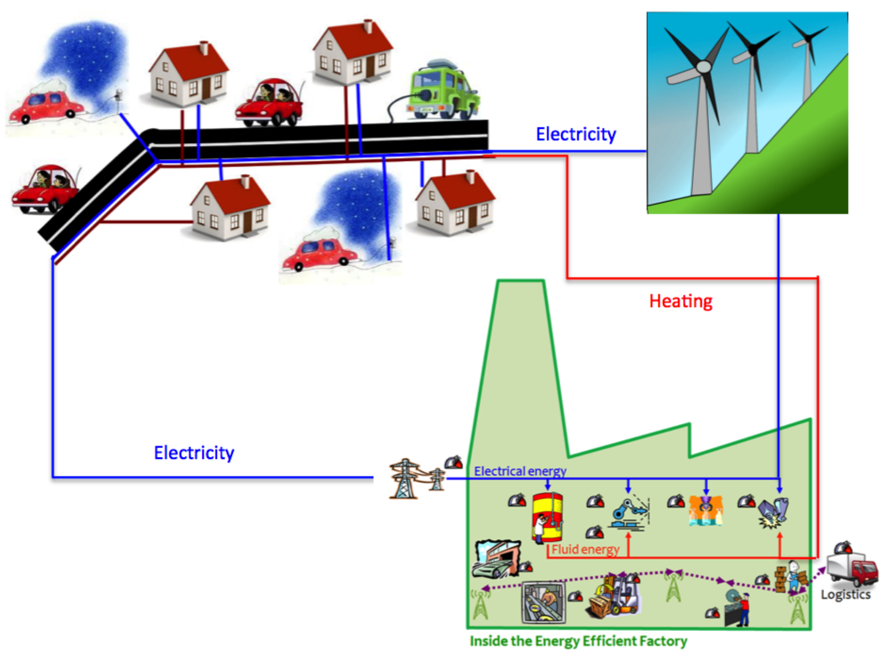

Fig. 11.3 A System of Systems view empowered by CPS for the energy domain

CPS are seen as a key part of critical infrastructures including the energy domain [8]. Future smart cities will integrate multiple such systems in a harmonized way in order to enable new innovative services for their citizens. Hence, factories will be situated within cities, smart buildings and smart houses will take full advantage of the energy available in the grid, and all forms of energy by-products such as heat will not be wasted but fully integrated e.g. for heating houses, public buildings etc. This vision is depicted in Fig. 11.3, which shows a system of systems from the energy viewpoint, whose key monitoring and control functionalities reside on CPS. As witnessed in Chapter 9 we have already shown how energy management can be achieved with enterprise considerations and in Chapter 10 we have presented some initial efforts for the integration of such systems. Although we are still at the dawn of the CPS era, it is clear the pivotal role that industrial CPS can play in the future. This vision is only realizable due to the distributed, autonomous, intelligent, proactive, fault-tolerant, reusable (intelligent) systems, which expose their capabilities, functionalities and structural characteristics as services located in a "Service Cloud" [14]. The infrastructure links many components (devices, systems, services etc.) of a wide variety of scales, from individual groups of sensors and mechatronic components to e.g. whole control, monitoring and supervisory control systems, performing e.g., SCADA, DCS and MES functions.

11.3 Challenges

For the new infrastructure to materialize and become a reality, several challenges need to be adequately addressed. We indicate here some key questions upon which more research and experimentation will need to be conducted in order to assess their impact on future industrial CPS systems, as well as the degree of their fulfilment that is required, especially for the critical infrastructures. We depict here some thoughts for consideration:

- *Management:* Considering the hundreds of thousands of devices only active in an industrial setting, e.g. a factory, or the millions of them in a larger one, e.g. a smart city, new ways of easily managing large scale and complex systems need to be considered. Dynamic discovery, interaction and exchange of information as well as lifecycle management especially over federated systems is challenging.
- *Security, Trust, Resilience, Reliability and Safety*: CPS have a real-world impact and control real-world infrastructures. Failures may result to havoc with escalated effects that may impact safety. To what extend such systems can be designed with security, trust and safety in mind, especially when operating as part of a larger ecosystem is not trivial [8]. The tackling of reliability of CPS ecosystems as well as that of resilience will be the key factor for their application in critical systems, or otherwise put, to what extend our core critical infrastructure will be vulnerable in the future [9].
- *Real-time Data Collection – Analysis – Decision – Enforcement*: For CPS to excel in their role, real-time collection of data has to be realised, and subsequently

analysis of it can help taking the appropriate business decisions, and enforcing them. Although CPS up to now had local decision loops, with the fusion with the cloud and the dependence on external services, the timely interaction aspects need to be revisited. A distributed collaborative approach is called upon here, where parts of the functionalities are hosted where it makes sense (on-device, in-cloud etc.) in order to guarantee real-time interactions from data-collection, to analysis, decision and enforcement.

- *Cross-layer collaboration*: CPS and their effectiveness will depend on the collaboration with other CPS and systems via a service based infrastructure as already analysed. However, such complex collaborations will have various requirements from the technical and business side that will need to be respected, depending on the application scenario. How to effectively empower collaboration via services and tools, including interactions in intra- and cross-domain, so that emergent behaviour can flourish in ecosystems of CPS is not an easy undertaking.
- *Semantic-driven discovery and interaction*: Discovering the right services based on functionalities they provide, being able to communicate and exchange interoperable data and built collaborations, is a key enabler for future CPS. However, how this can be realised for multiple domains, dominated by a plethora of heterogeneous (in hardware and software) systems and services is a grand challenge.
- *Application Development based on generic CPS APIs*: CPS APIs reflecting the core functionalities need to be present and offer standardized interactions upon which more complex behaviours and services can be built. This will act as an enabler in the short-term until the semantic-driven interaction is fully tackled. Applications and services can then built upon the minimum services offered by the CPS itself as well as its envisioned supporting infrastructure (CoT) and extend them.
- *Migration and Impact of CPS to existing approaches* The introduction of CPS will ignite a rethinking on various levels at the infrastructure itself as well as the processes that depend on it. However, assessing the exact impact on a larger scale system might be challenging and has to be carefully investigated. As CPS will gradually replace legacy approaches, strategies for the migration of legacy systems to the CPS ones are needed. To this end, simulators/emulators of systems and behaviours are also needed to assist with the assessment of transitions.
- *Sustainable Management* Cloud-based CPS bring the promise for more efficient usage of the globally available resources as well as optimisations from various perspectives, e.g. execution, communication, interaction, management etc. Hence more sustainable strategies for managing infrastructures and businesses may be realized e.g. energy-driven management [12]. Such efforts should be seen on a greater context, i.e. cross-enterprise, smart city-wide etc. Tools and approaches that will empower us to integrate such approaches effectively in large-scale CPS are needed.
- *Development and Engineering Tools* Development and Engineering tools and environments will be a must in order to ease the CPS ecosystem service creation and orchestration/choreography within complex environments. Cross-platform availability and capability are seen as key aspects for offering sophisticated ser-

vices. These tools will need to be coupled with appropriate "wizards", debugging capabilities (at local and system-wide level), as well as simulation environments where 'what-if" approaches can be realized.

- *Data Lifecycle Management & Sharing*: Being able to acquire the data from the physical and cyber world is the first step. Sharing them in order to built sophisticated services and effectively managing them is a grand challenge. The latter has to be done with consideration of the operational context its requirements for security, privacy, etc. while in parallel enabling their wide availability, e.g. as open data in appropriate forms for other parties to extract information for their processes. Although the specific business needs and requirements have to be satisfied, data from CPS will be a commodity in the years to come, and will be traded as such.
- *Data Science on CPS-empowered Big Data* The massive CPS infrastructures envisioned and their fusion with the Cloud, will lead to massive amounts of data acquired for the finest details of a process. This "Big Data" can be analysed in the cloud and provide new insights for the industrial processes that may lead to better enterprise operations and identification of optimisations. Data science approaches on the available Big Data is expected to have a wide impact on the way we design and operate CPS infrastructures.

Industrial Cyber-Physical Systems are changing the economy and society [1]. Therefore, in addition to the key challenging aspects raised above, one has to always bear in mind that CPS will have to address the human factor adequately in order to be successful. This puts a spotlight on another set of challenges such as:

- *Education*: Due to the complexity and sophistication of CPS and the domains they are applied, a new generation of engineers will have to be educated on a variety of aspects pertaining several domains. This implies cross-disciplinary skills that successfully fuse application domain specific knowledge, CPS engineering as well as HCI skills that will need to be continuously maintained (life-long learning). Such programmes should be introduced at Universities at graduate and post-graduate levels including specialisation on CPS technologies.
- *Training*: The industrial adoption of this new paradigm represents a revolution that requires advanced skills and extensive training activity. Architects, Engineers and Operators at first level, will need to be re-educated for dealing with heterogeneous physical and cyber systems, as well as fully understand their capabilities, benefits and challenges they offer. Simulation/Emulation and hands-on experiences are considered pivotal towards tackling this challenge.
- *Thinking shift*: The benefits can be tremendous in B2B, B2C, B2B2C etc. and grasping the potential as well as correctly assess the risk associated means that not only new business models should be developed, but increasingly focus on the human role in these as an end-used of a CPS (either directly or via the surrounded infrastructure). Decision-makers, industrial strategists, legislators and policy-makers will have to consider a balanced action for empowering innovation without falling short on privacy, usability, espionage, security and trust.

11.4 Conclusion

We have presented a vision, some major trends that will reshape the way we design, implement and interact in future industrial CPS-dominated environments, especially when it comes to monitoring and management, as well as some key challenges and considerations. The fusion of Cyber-Physical Systems with the cloud is still at a very early stage. However, it has profound implications as it blurs the fabric of cyber (business) and physical worlds. Time-sensitive monitoring, analytics and management will be of key importance for any real-world application. As such emphasis should be given to the basic parts of such collaborative CPS ecosystems in order to act as enablers towards the vision realisation. The considerations raised here for CPS to be used in Industrial applications, are in the same line of thought with the recommendations for action [1] for the successful introduction and widespread adoption of CPS in general. Only then key Industrial visions such as the Industry 4.0 [7] can materialise.

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