Cyber-Physical Systems in the SmartGrid

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***Abstract*—Radical changes are expected to occur in the next years in the electricity domain and the grid itself which has been almost unchanged the last 100 years. Value is created when interactions exist and this is the main thrust of the emerging SmartGrid which will heavily rely on IT technologies at several layers for monitoring and control. The basic building blocks are the existing efforts in the domain of the Internet of Things and Internet of Services, that come together with cooperation as the key enabler. The SmartGrid is a complex ecosystem of heterogeneous (cooperating) entities that interact in order to provide the envisioned functionality. Advanced business services will take advantage of the near real-time information flows among all participants. In order to realize the SmartGrid promise we will have to heavily depend on Cyber-Physical Systems (CPS) that will be able to monitor, share and manage information and actions on the business as well as the real world. CPS is seen as an integral part of the SmartGrid, hence several open issues will need to be effectively addressed.**

I. Introduction

It has been shown that value is created when interactions among people, businesses and generally entities exist. For these interactions to happen, networks are formed that operate with their own rules over an infrastructure. The electricity grid is such an infrastructure connecting however entities with very limited interactions among them – up to now.

Today's grid features a typical centralized approach where few powerful central stations broadcast energy to the different consumers. However as renewable energy resources pave their way, we expect that future users will not be simply consumers of energy but also producers; hence the term "prosumers" has been coined to reflect the ability to interchangeably slip to these roles. The smart grid [1], [2] is an emerging concept targeting to provide the next-generation electricity network that will boast advanced configurability, reactiveness, and self-manageability. It is a complex infrastructure depicting system of system characteristics [3] such as interdisciplinary nature, operational and managerial independence of its elements, geographical distribution, high heterogeneity of the networked systems as well as emergent behaviour and evolutionary development. It is expected to be the key part in a global ecosystem of interacting entities, whose cooperation will give birth to innovative cross-industry services. One of the key driving forces behind these efforts is energy efficiency and better management of the available resources (locally and globally). In order to achieve this, fine-grained monitoring and management is needed.

Cyber-Physical Systems (CPS) [4] represent an amalgamation of computational and physical properties and can be found extensively in multiple domains including the electricity grid. In the last decade technology innovations have pushed further the limits, blurring the distinction between the real world and the virtual one by using networked embedded devices that offer real time information exchange between them. Decreasing in size but with continuously increasing communication and computation capabilities, these ubiquitous devices offer advanced monitoring and control of real-world processes at an unprecedented scale. Modern businesses rely on CPS to accurately sync the real world status on backend systems and processes.

The core idea behind the amalgamating the physical and virtual (business) world is to seamlessly gather any useful information about objects of the physical world and use the information in various applications during the object's entire life cycle. Collecting information and making it available, for example, about the objects' and goods' origin, location, movements, physical properties, usage history, and context, can help enterprises improve both existing intra- and inter-company business processes and also create new ones. Existing business processes may become more accurate since information taken directly from the point of action can be used to enhance decision-making procedures. The continuous evolution of embedded and ubiquitous computing technologies, in terms of decreasing costs and increasing capabilities, may even lead to the distribution of existing business processes not only to the network itself but also to "network edges" i.e. the CPS, and can overcome many limitations of existing centralized approaches.

Researchers (and not only) have had various motivations, hence various names such as Internet/Web of Things/Objects [5], Cooperating Objects [6], Cyber-Physical Systems [7], networked embedded systems etc. have emerged, and although one may argue on the differences and their focus, they all refer to the amalgamation of computation and physical properties; hence we do not really differentiate when we refer to them in this paper.

II. CPS Market Expectations

To have a view on the potential impact of CPS one can consider (with a grain of salt), industry views and predictions. Especially on the mobile and pervasive CPS, expectations and stakes are high. According to Håkan Djuphammar, VP of systems architecture at Ericsson, "[In 10 years' time], everything has connectivity. We're talking about 50 billion connections, all devices will have connectivity...". This was reinforced by the Ericsson President and CEO Hans Vestberg who mentioned that 50 billion devices will be connected to the web by 2020. Intel's John Woodget, global director in Telecom sector has a more moderate prediction, in the range of 20 billion connected devices by 2020 [8]. Getting down to the SmartGrid specific projections, Marie Hattar, VP of marketing in Cisco's network systems solutions group, estimated in 2009 that the SmartGrid network will be "100 or 1000 times larger than the Internet" [9]. Similarly Vishal Sikka, CTO of SAP, stated in 2009 that "The next billion SAP users will be smart meters" [10].

Typical SmartGrid CPS example are the smart meters, and only for installing them at homes an estimated $4.8 billion will be spent according to ABI Research [11]. According to Pike Research the market for energy management systems (including wireless sensor networks, lighting controls, heating and cooling management in buildings) will turn into a $6.8 billion a year market by 2020 and will generate investment of $67.6 billion between 2010 and 2020 [12]. They also note that a total of $4.3 billion will be spent on the installation, maintenance, and management services for smart grids by 2015 [13]. The smart home is within the heart of energy aspects of SmartGrid (where both energy monitoring and management are applied). In 2012, the Wireless Sensor Network smart home market will be worth $2.8 billion worldwide, up from $470 million in 2007, estimates electronics.ca Research Network . The smart home is becoming a reality for the mass market as hundreds of products currently shipping and established service providers such as AT&T and SK Telecom are starting to offer WSN based home monitoring services.

The modern mobile devices are another prominent CPS. Especially the latest generation of smartphones and tablets feature various sensors while providing a powerful communication and computation platform. According to Gartner [14], the total number of PCs in use will reach 1.78 billion units in 2013. By 2013, the combined installed base of smartphones and browser-equipped enhanced phones will exceed 1.82 billion units and will be greater than the installed base for PCs thereafter.

These are just some market estimations depicting the fact that we are still at the dawn of a new CPS-dominated era. Already today multi-million research and deployment projects are under-way worldwide, investigating aspects of the SmartGrid including its CPS nature.

III. Technology Trends

We are witnessing today several technology trends that may have a significant impact when designing and implementing solutions on cyber-physical infrastructures such as the SmartGrid. The electricity network is a critical infrastructure, hence timely high-quality information acquisition, context assessment, decision-making and actuation needs to be open [15], streamlined and dependable. Considering its complexity and dynamic interactions, modelling the SmartGrid [16] and assessing the tremendous amount of information generated by the future heterogeneous CPS dominated infrastructure, is a very challenging task. Integration and cooperation are major goals especially for a domain relative new to IT technologies and their rapid evolution pace. Interoperability and security may be show-stoppers if not done right from the start (where we are now).

Information Driven CPS Integration: Business systems nowadays heavily depend on high-quality information from the real world. CPS might assist by providing that link i.e. dynamically discover, integrate, and interact with the real world. The service oriented architecture (SOA) empowered CPS may point us towards a potentially right direction. By abstracting from the actual underlying hardware and communication-driven interaction and focusing on the information available via services, we move towards a service & information driven interaction. By accessing the isolated information and making the relevant correlations, business services could further evolve, and dynamically integrate real-time feedback from the real physical-domain services (both for monitoring and control).

On-CPS Business Process Execution: In an CPS-dominated infrastructure huge amount of information is generated. Transmission to a central location of necessary data in order to extract the gist may not be optimal and the enterprise systems are not designed for such operations today. Hence business processes that require data residing on a CPS could outsource that part of their functionality to run directly on the CPS or a collocated system (depending capabilities and characteristics e.g. communication, computation and possibly spatial constraints). Distributing load in the layers between enterprises and the real world infrastructure (distributed business process) is not the only reason; distributing business intelligence is also a significant motivation.

Cooperating CPS: Most of CPS today rely on operating in standalone manner or provide information to standalone services. However with the increased communication and emergence of networks of CPS they will be able to cooperate, share information, act as part of communities and generally be active elements of a more complex system [17]. By doing so they may be able to tackle aspects envisioned for the SmartGrid such as self-management, self-optimisation, and self-healing. As such the governing logic may be expressed in a goal oriented manner assigned to networks of CPS aiming at satisfying business process requirements.

Virtualization and Utility Computing for CPS: In the IT world we witness a trend towards virtualization of resources such as hardware platforms, operating systems, storage devices, network resources etc. Virtualization addresses many enterprise needs for scalability, more efficient use of resources, and lower Total Cost of Ownership (TCO) just to name a few. CPS may be directly affected by this trend as now functionality provided by a single standalone CPS can "roam" the network of CPS devices, to optimally execute depending on abstract provided resources residing both on the physical world (e.g. available sensory instruments) as well as the IT world (e.g. cloud available computing power). Important is also that although the CPS may not have the capabilities required by itself, it can extend these by collaborating/outsourcing computational aspects to services in the cloud and possibly physical tasks to nearby CPS equipped with the required capabilities e.g. sensors/actuators.

Multi-core and GPU computing for CPS: Assessment of the huge amounts of data generated by the SmartGrid will be challenging and require significant processing power. Since 2005 we have seen the emergence of multi-core systems, that nowadays exist also in CPS e.g. dual-core powered android smartphones. The general trends is 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 CPS. 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 applications this may mean a performance increase to several orders of magnitude when compared with a conventional CPU. Furthermore a recent trend of integrating built-in graphics capabilities with processors (graphics-enabled microprocessors – GEM) like Intel's Sandy Bridge and AMD's Fusion, may imply that capabilities of GPU computing may be available to any kind of device hosting one of those processors. Such a CPU/GPU hybrid can possibly be even more efficient by removing the slow communication between CPU and GPU. The processors with built-in graphics capabilities to be installed in 2011 on 115 million notebooks account for half of total shipments. By 2014, 83% of the world's notebooks and 76% of desktops will ship with graphics-enabled microprocessors [18]. This in practice implies that CPS equipped with such technologies may increasingly possess significant computational power, be more energy efficient, and possibly execute high performance stream processing e.g. on metering data at the point of action.

SOA-ready CPS: The SmartGrid is by its nature highly heterogeneous, and so are the majority of CPS it relies upon; we don't expect this to change. The latest trend is to enable CPS to offer their functionality as one or more services for consumption by other entities. 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 the device layer [19]. This could greatly enhance interoperability and lead to independent layered development at software (potentially also to hardware) side. Furthermore the integration is done via the capabilities offered (as services), while the actual implementation is hidden.

IV. Discussion on Emerging Directions

The SmartGrid is an ecosystem which will heavily rely in its basis on (real-time) information acquisition (monitoring), assessment and decision making as well as management (control). Many traditional parts of the SmartGrid are increasingly CPS dominated. In generation CPS control the connection to the network as well as the operational aspects in the electricity generation side such as solar and wind parks, hydro facilities etc. For instance SCADA and DCS systems are responsible for monitoring and control of power plants. In transmission and distribution networks that connect end-users to the SmartGrid, CPS monitor its conditions and care for its stability. CPS e.g. substations, smart meters, concentrators, intelligent field devices etc. are used to manage the bidirectional communication. On the customer side e.g. in homes, commercial/industrial buildings and infrastructures, CPS manage the energy as well as other automations (e.g. air flow, temperature etc.). Here the most prominent example of CPS are the smart meters that control and measure the flow of electricity and the energy management systems (EMS). With the emergence of electric mobility (several plug-in vehicles are on the market today) and the distributed installation of small-scale generators (e.g. solar panels) the SmartGrid prosumer (producer and consumer) will heavily depend on CPS. Additionally CPS are used to fine-tune the connection as well as the information exchange among the various entities. On the operation side CPS is used increasingly for monitoring, reporting, controlling and supervision.

One key issue that the SmartGrid is advocating is the creation of interactions among its different actors. One way to facilitate these interactions is via online energy marketplaces. These will allow trading of energy and interaction with value added services e.g. billing, roaming, inter-utility exchange etc. The majority of these are expected to be automatic e.g. via intelligent user-configured agents and smart CPS. These will have to monitor user's context (e.g. preferences, current location, capabilities, existing contracts etc.) and take automated decisions on his behalf. Investigation of the dynamics will need to be carefully studied. Among other things spatial location as well as information acquisition, in-network processing and propagation will play a key enabling role.

Parts of the SmartGrid will be managed by safety-critical applications, whose development will be increasingly challenging. Since they will depend on various services it will be difficult to do holistic code reviews, systematic testing and checks at design and runtime. Hence, software "bugs" which may have a tangible impact on the physical world will happen more often while their impact will be hard to be assessed. It is not clear how much effort will need to be invested on designing and integrating software for such complex system of systems versus testing it, as well as the qualifications that future engineers will need to possess to do so. Automatic tools that do the model checking as well as detect potential safety-critical issues on large scale multi-dimensional applications will be needed.

Design of applications will become increasingly challenging mainly due to the multi-domain interactions and constraints that will need to be satisfied at several layers. CPS will have additionally to both support computational as well as physical requirements. For instance a change on the security policy may lead to redesign of the interactions among the different entities. This may imply significant CPU utilization on the CPS and potentially drain its resources, hence minimizing its lifetime or affecting the QoS of the delivered services. It will be increasingly difficult to assess how design decisions in one part of the SmartGrid may have an effect on depended services and applications, especially since most of them will be developed and maintained by different entities. Modelling, risk analysis and impact assessment tools for complex systems will be needed to guide us and provide Key Performance Indicators (KPIs) e.g. related to reliability, safety, performance, resource impact, quality etc.

Standardized abstractions among the various layers and open architectures for CPS-enabled SmartGrid systems is needed. These should enable scalability and component/layer independent evolution. Additionally it should be possible to use highly configurable components and combine them with guarantees e.g. wrt. to performance, safety, dependability etc. These of course should be assisted by a fully-fledged lifecycle framework on a SmartGrid wide system so that new functionality can be managed easily.

Mobility is a prominent issue in SmartGrids. Apart from the obvious plug-in vehicles, it is expected that in the future any device that consumes or produces energy will be able to provide this information for others to use. The majority of them are expected to be mobile; hence the future CPS will be composed of mobile elements and functionalities that will need to be able to handle such a dynamic environment both in software as well as in hardware. It will be the role of the infrastructure to appropriately support mobility at all layers and its side effects e.g. data replication, session management, application semantic considerations etc.

Security and Privacy [20] are potentially show-stoppers for the CPS SmartGrid since now more than ever user actions can be monitored or devised from the data. Additionally since this is a critical infrastructure one should take extra precautions to tackle highly sophisticated attacks. Recently the Stuxnet worm successfully demonstrated the feasibility of a very targeted and highly sophisticated cyberwarfare [21] attack. Hence it is imperative to invest on the security as a process by looking holistically the emergent CPS-dominated SmartGrid.

The CPS-enabled SmartGrid is in need of solutions that will support it at device, system, infrastructure and application level. This includes the whole lifecycle from cradle-to-grave of its components and its services. This is a grand challenge and includes multi-disciplinary engineering, modelling, emergent behaviour, human interaction etc.

V. Conclusion

Cyber-Physical Systems lie in the heart of the emerging SmarGrid. Their abilities on providing the "glue" between the physical world and the business side makes them indispensable. However several issues remain open and significant efforts will be needed to understand how CPS can operate within a complex system of systems such as the SmartGrid as well as the impact of their interactions and cooperation in a network of CPS. Significant research will be needed towards integration of control for networked embedded systems, large scale monitoring, simulation, high-performance analysis and cross-layer modelling and integration.

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