Intelligent and Collaborative Embedded Computing in Automation Engineering

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***Abstract*—This paper presents an overview of the the novel technologies that we are experiencing today in the automation industries. We present the opportunities and challenges of having tightly coupled collaborative networks of embedded systems for controlling complex physical processes. Our objective is to motivate the targeted design automation community to tackle some of the grand challenges in the area of such a distributed, intelligent, and collaborative embedded computing platform.**

I. Trends in Automation Engineering

Automation technology (sensors, actuators, controllers, and embedded software) is one of the pillars sustaining the world population. All sectors including industry (production and manufacturing of food, medicine, semiconductors), energy (hydro-electric, nuclear), healthcare (elderly, diagnostics), infrastructure and cities (smart transportation, intelligent buildings) have become highly efficient due to the advances in the automation technologies that bridge the gap between the physical processes and the information systems.

Computing devices continue to follow the Moore's Law and on every generation, smaller and more energy-efficient high-performance processors can be embedded in sensors, actuators, and more functional controllers. Moreover, embedded multi-core processors with better performance/Watt characteristics are already available in the market and waiting to be integrated in the mainstream automation applications for ground breaking innovations. As of 2011, the industrial automation electronics equipment world market (excluding software and services) is estimated to be worth approximately $97 billion [2]. While software has been crucial for bringing *intelligence*[1] to these systems, it is also becoming a serious problem due to its increasing complexity [1]. Communication technologies have also advanced enormously. Internet is the perfect example of how activities can be completely reshaped when things start to communicate and interact in meaningful ways. However, not until recently, communication is becoming a priority in the automation engineering sectors. The automation technologies and therefore all industries, are migrating from loosely coupled configurations to tight couplings of computation, communication, and physical processes. This tight integration is happening at all scales of technology.

Multi-core architectures have facilitated the co-existence of multiple independent embedded systems in the same die. On-chip communication (for detailed micro-scale integration see Sec. III) facilitates the integration of heterogeneous (non-)real-time systems and improves the overall life-cycle cost, performance, reliability, power efficiency, and response times. At a higher level of integration, geographically distributed embedded devices (sensors, actuators, and controllers) are being connected using wired/wireless technologies and forming an *intelligent* and collaborative computing platforms (for detailed macro-scale integration see Sec. II).

[1]In this paper we define *intelligence* as the ability of a system to globally optimize a process through the collaborative communication of its parts.

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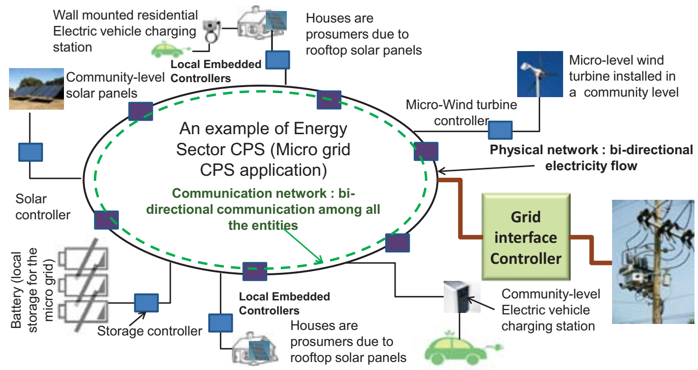

Fig. 1: Large-scale intelligent CPS in the energy sector

II. Cyber-Physical System Perspective

Intelligence in automation components is enabled by **embedded software** and **communication** and without them it would be impossible to control large-scale distributed physical processes. *Cyber-Physical Systems*, or CPS, are physically distributed embedded systems connected through various types of wired/wireless communication technologies (e.g. ZigBee, Cellular, WiFi) that collaborate to accomplish the functionality of highly integrated control systems.

Energy applications are a good example that illustrates how the need for quality, reliability, cost, environmental impact, and renewable sources are pressure points for moving from the legacy power infrastructure systems (centralized) into a more intelligent power distribution network. The use of digital communication among various electric network components (e.g. generators, end-user appliances, meters) enables a bi-directional flow of electricity allowing consumers to become active producers by incorporating renewable sources (e.g. solar panels in a household). The paradigm shift to a more *intelligent* energy grid is known as "smart grid" [3]. The smart grid initiatives across the world are converging in the following applications:

1. Building automation. Currently focused on industrial and commercial buildings but we also expect the residential domain to become popular in the following days. Research on intelligent scheduling algorithms to balance the electric load based on pricing signals is necessary to enable a compelling and affordable solution. Moreover, these systems must take into account the management of electric vehicle loads (which is comparable to the total load of a house) within the residential and the distribution grid infrastructure.

2. Micro grid. A localized group of electric sources (including renewable sources) and loads (typically operating in a centralized grid) that needs to be managed in a decentralized way to allow autonomous operation (Figure 1). New agent-based distributed algorithms are required to implement such a highly distributed CPS application.

3. Demand response application. For the efficient and collaborative management of daily peak load demands between producers and consumers without major investments in additional infrastructure. This CPS application may be built based on incentives and penalties for the consumers. For example, a payment on kilowatt savings of electricity through shedding some larger loads for some time frame or pricing higher on usages during peak demand.

All these energy-related applications require significant research activities in the areas of novel embedded systems, system modeling methodologies, automation development tools, lightweight communication protocols capable to be hosted on embedded devices, real-time scheduling algorithms, multi-objective optimization algorithms, negotiation algorithms based on monitored data among the participating entities, and middleware development for hiding the heterogeneity of the computing devices.

III. Multi-Core Virtualization

Multi-core technology satisfies the key requirements for the next-generation industrial automation: fast communication through specialized interconnection networks, computation scalability and redundancy through many CPUs, low cost, high reliability, long life-cycle, and energy and thermal efficiency. Despite all these advantages, we believe that the most important innovation to come from this technology is **virtualization**. Component-level virtualization is now possible with multi-cores because the essential automation components (i.e. controllers, sensors, *Human-Machine Interface* (HMI), actuators, etc) may be hosted in the same processing unit and thus the total number of elements will be reduced. In addition, low-latency high-throughput on-chip communication is available for these components and therefore novel and *intelligent* services may be developed. On the other hand, system-level virtualization is accomplished due to drastically reducing the number of components and the complexity of the system. Therefore, less processing elements, batteries, energy, maintenance, wiring, and weight are required. Moreover, these systems will provide *massive redundancy* at low cost where some components are easily replaceable by software which making them highly reliable, survivable, and longer-lived.

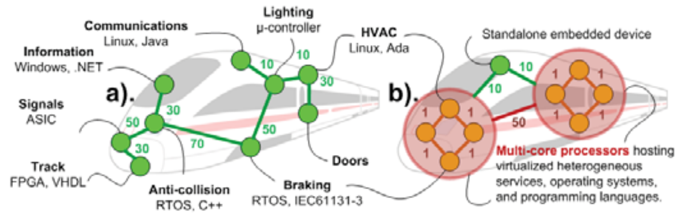

Fig. 2: Embedded software and hardware virtualization in multi-core will enable more *intelligence* and efficiency in CPS applications such as high-speed trains.

Modern high-speed trains contain a large number of embedded controllers, signal processors that operate on thousands of inputs and outputs, multiple HMIs, sensor and actuators, and communication devices. Currently, the computational fabric of these trains is implemented with standalone processing units that are loosely connected through industrial-strength communication networks (See Fig. 2(a)). Multi-core technology simplifies the networks and improves the overall performance of the system because virtualized embedded devices can be hosted in the same chip (See Fig. 2(b)). On-chip communication not only improves the communication speed by more than an order of magnitude between tightly coupled components but also reduces the system-level network latency due to less traffic, the life-cycle cost due to decreased maintenance, replacement, and installation. However, **heterogeneity** of software and hardware components is the inhibiting challenge for adopting multi-core. The reality is that a wide variety of operating systems, programming languages, computing elements are used and therefore creating a homogeneous hardware and software architecture that "fits all" would be economically and technically impossible. Instead, new ideas in **virtualization of embedded software and hardware in multi-core processors** as well as code generation for distributed heterogeneous systems are needed.

IV. Summary

We are in the verge of a new era of multi-disciplinary real-time embedded systems where communication and collaboration among all the subcomponents is the key for the system-level collective intelligence. Large-scale distributed physical processes may now be handled more efficiently, economically, ecologically, and smartly. At the same time, in a micro-scale level, faster on-chip communication and multiplicity of computing instances within the multi-core facilitate virtualizing the system to allow co-existence of various heterogeneous systems. This component-level virtualization is proving to be efficient, economic, reliable, and thermal efficient. Besides other research challenges already mentioned earlier, we believe such a system is going to face potential security and privacy treads.

References

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