Modelling cyber-physical systems: some issues and directions

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Abstract. On the context of industry 4.0 there are still huge gaps, in several areas, and some scientific and technological challenges are addressed in the domains of sensing, communication, computing, cognition and autonomous control. In this paper there are discussed some issues on modelling cyber-physical systems, as well as possible directions to follow, in this aspect, for obtaining correct specifications for distributed controllers' systems. This work is focused on the main issues considering plant modelling approaches.

1. Introduction

With the increasing evolution of information technologies and electronics, started the beginning of the fourth Industrial Revolution through the concepts of cyber-physical systems (CPS) [1] and Internet of Things [2] and services. The integration of cybernetic technologies that make products with Internet access facilitated innovative services to achieve, among other things, diagnostics based on Internet, maintenance, operation, etc. economically and efficiently. In addition, it helps to realize new business models, operational concepts and intelligent controls, and focusing on the user and their individual needs. The goal of Industry 4.0 is the emergence of digital factories.

In the industry 4.1, development of industrial machines presents major challenges, as it presents a paradigm shift [2], [3], namely:

- Development capacity increasingly becomes essential for business success; high degree of individualization requirements, It is increasingly the customer to define the rules of commercial exchanges that takes a high degree of individualization of the products;
- Flexibility, high degree of flexibility is required in the developed products and the production lines;
- Decentralization, fast decision systems have to be developed, for this the hierarchies must be reduced;
- Efficient use of resources, due to the growth of raw materials and the growth of environmental policies, leads to the search for greater sustainability.

This has led to a technological push towards an increasing increase of mechanization and automation, more and more systems are developed to support physical work. Another of the affected areas and information systems, increased digital capacity and networking are sought to develop tools to support manufacturing and quality control.

According to [1] and [4], which present an industry application architecture 4.0 composed of five different hierarchies (see Figure 1).
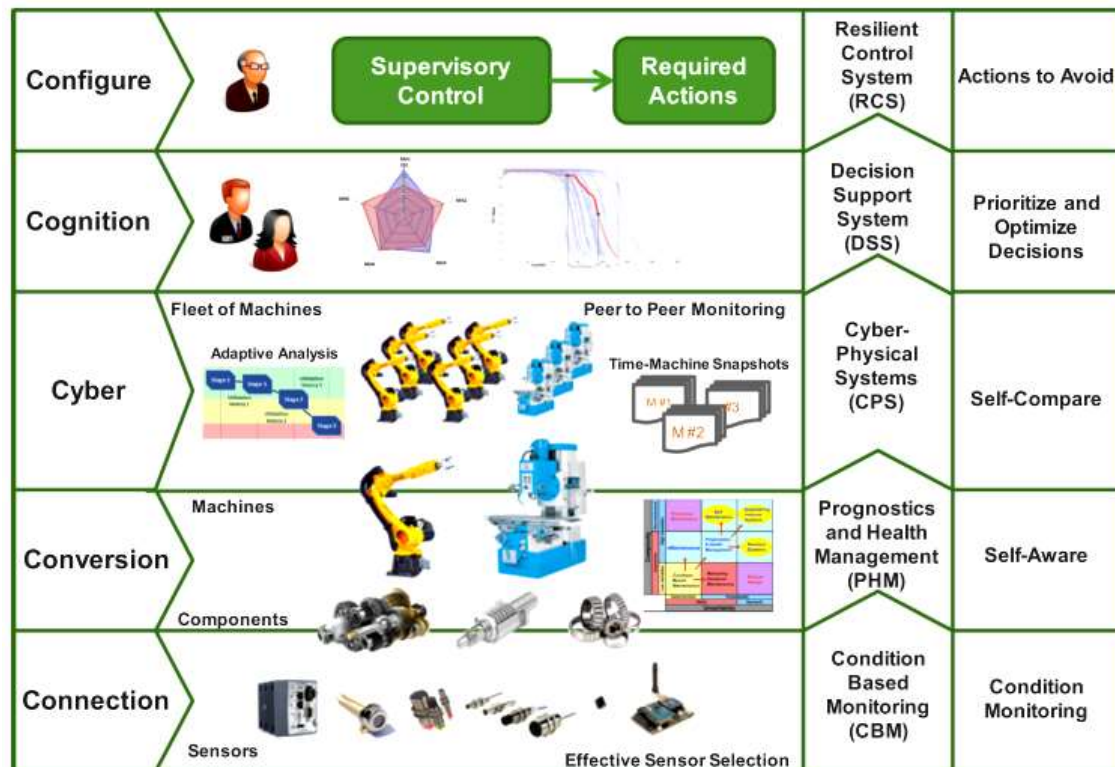
Figure 1. techniques and applications associated with the 5C architecture.

Basically, there are 5 layers / architectures:
- Connection: performs data acquisition of machines and their components;
- Conversion (of information): as the name implies, it treats the acquired data in the lower layer, transforming it into information that can be analyzed to obtain conclusions about the functioning of the systems;
- Cyber: this is the information concentration layer, where the virtual model of the system is elaborated. Once the data is concentrated, algorithms that analyze the operation of the system are applied;
- Cognitive: at this level the results of the previous layer are analyzed and formatted to be presented to trained personnel;
- Configuration: The last layer of the model serves as a return of the virtual environment to the physical, acting as a system of control and supervision need to be done.

Implementing CPS in today's factories offers several advantages that can be categorized into three component stages, machines and production systems. Considering a production line with many machine tools, the advantages of a CPS company enabled in the above-mentioned steps can be observed. At the component stage [4], once sensory data from critical components have been converted into information, a cyber-twin of each component will be responsible for capturing time machine records and synthesizing future steps to provide self-awareness. In the next stage, more advanced machine data, e.g. parameters, would be aggregated to component information to monitor status and generate the cyber-twin of each machine. These machine twins on CPS provide the additional Auto Comparison capability. In addition, in the third stage (production system), aggregate knowledge of components and machine level information provide autoconfiguration and self-maintenance for the factory. This level of knowledge not only guarantees a free and trouble-free production time, but also offers optimized production planning and stock management plans for the factory. The expectations for CPS are immense: versatility, robustness, autonomy, self-organization,

self-maintenance, self-repair, transparency, predictability, efficiency, interoperability, tracking, just to name a few.

Although there are very important developments in cooperative control, multi-agent systems, complex adaptive systems, emerging systems, sensor networks, data mining, etc., even a partial fulfilment of these expectations would represent challenges, namely [5], [6]:

- New theoretical results should be achieved and the development of efficient algorithms for consensus-seeking, cooperative learning and distributed detection is required;
- Identification and prediction of dynamic systems. It requires an extension of the methods of identification and prediction available, as well as the development of new ones that can be applied under soft assumptions in the dynamic system as well as the disturbing process.
- Robust programming. New results should be achieved in the treatment of production disturbances in the course of programming.
- Fusion of real and virtual systems. It is necessary to develop new structures and methods that support the merger of virtual and real subsystems to achieve a smart production system robust in a changing, uncertain environment. New reference architectures and models of integrated subsystems of virtual and real production; the synchronization of virtual and real modules of production systems and their specific interaction of function; and efficient, resource-efficient factory floor control algorithms are needed;
- Human-machine symbiosis (including human-robot). It is necessary to develop a geometric data structure for the fusion assembly features and sensor measurements and fast search algorithms to adapt and compensate for dynamic changes in the real environment.

In the domain of the CPS there is a great deal of opportunities for researching, as was mentioned above, so there is a lot to be done is several areas. This paper is focused on studying (first insights) of the importance of the physical interference when developing the specification for controlling cyber-physical systems. In this domain there are a lot of aspects for being considered and a lot of work must be performed.

Section 2 discusses some issues related with plant modelling when considering different domains concerning modelling time aspects; section 3 proposes some future directions for research in this domain and section 4 presents some conclusions about ongoing work that is being developed by authors of this paper.

2. Plant Modelling

Considering the plant model, there is still a gap concerning the interaction of the Physical part with control unit on the context of industry 4.0 that uses the symbiose of the physical a and cyber world in an enormous scale is imperative the need to realise studies in this area.

There are two main areas of studies, concerning plant modelling:

- Discrete-Event or Timed Discrete-Event approaches;
- Continuous-Time approach.

2.1. Plant Modelling considering Discrete-Event or Timed Discrete-Event approaches

Usually, plant is modelled considering a modular approach. Some works have been performed; for instance, Pacheco and his team [7] where the development of the plant models for formal verification is discussed. This plant model approach using a modular approach was first present by Machado et al [8]. The work of Pacheco attempts to authenticate the results using a simulation bench and proposes a model for a lifting system (a module illustrated in Figure 2), according to the plant model proposed by [9].
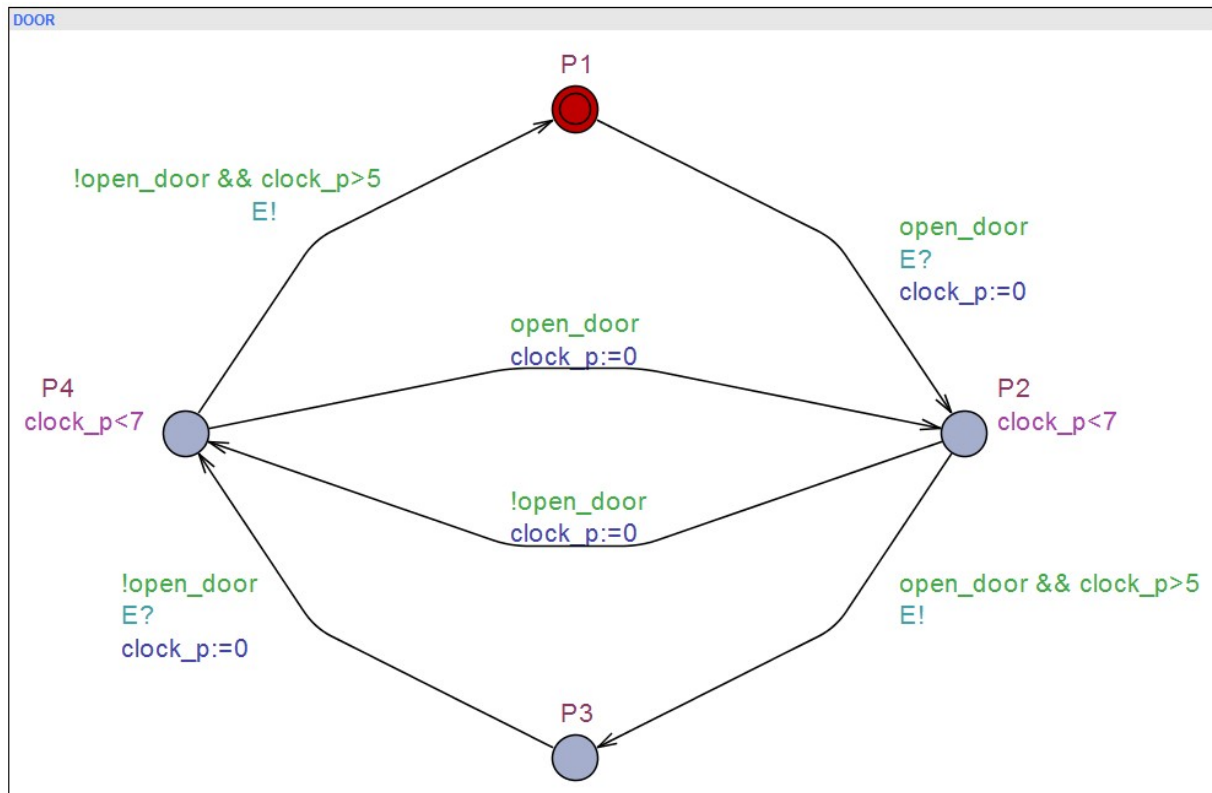
Figure 2. Timed automata model of an elevator door [7].

The same modular technique is used to model a parking lot by Machado and Galvão [10] and also by Canadas and his working team [11], on the domain of simulation.

Other work is proposed by Buzhinsky and Vyatkin, [12], [13] where a model for pneumatic cylinder is proposed, illustrated in Figure 3.
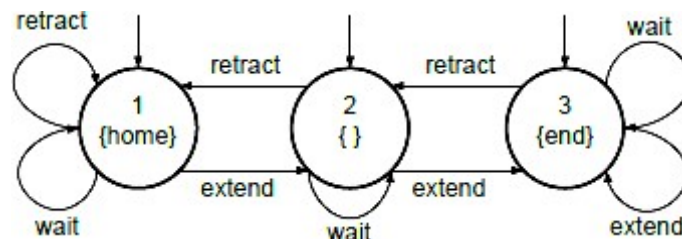

Figure 3. Plant model representation of [12] in NCES (Net/Condition Event System).

This mentioned work shows that there is still a gap for formal verification considering the plant model and they try to solve it. They propose NCES [15] and evaluate the model using checker tools, such as the visual verifier ViVe/SESA[16] formerly implemented for this study. Other approach using the same tools was developed by Sorouri, Patil, Salcic and Vyatkin [14] to test the decentralized controller Function Blocks discrete-event dynamics of the plant software composition method for automated machines that exploit their mechatronic modularity. They follow IEC 61499 Function Blocks' (FBs) architecture. As case study, the proposed approach is used in pick-and-place manipulator with decentralized control synthesized (**Error! Reference source not found.**4).
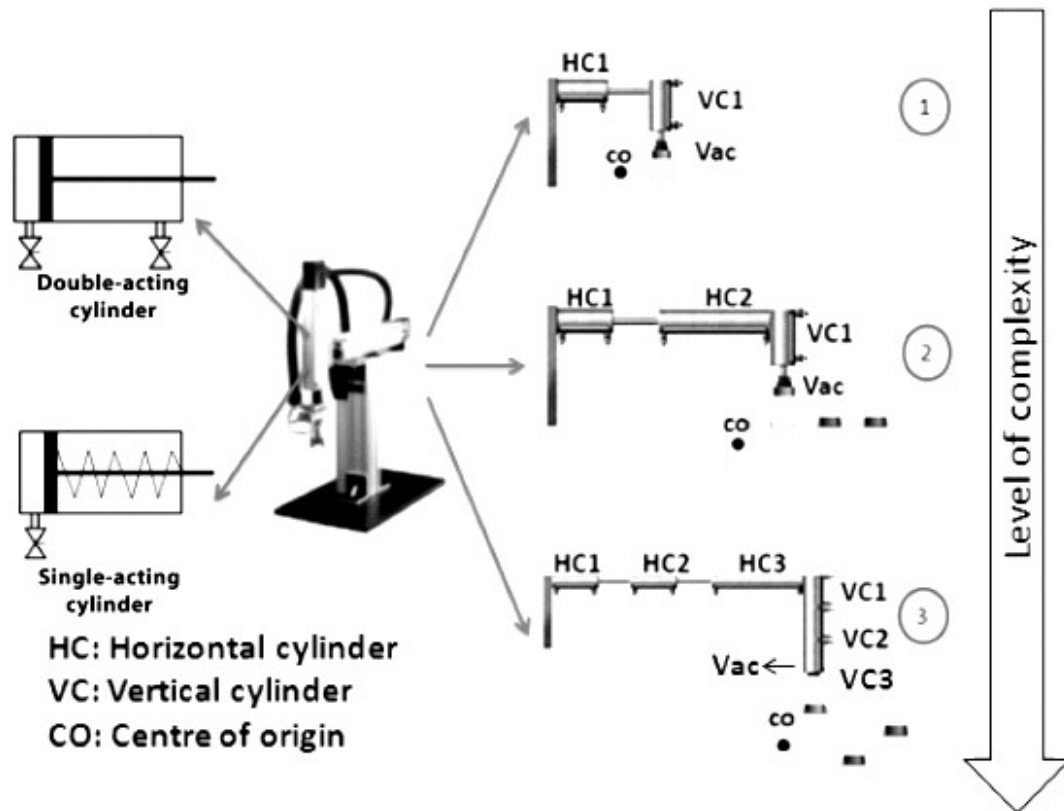
Figure 4. Plant model representation of [12] in NCES (Net/Condition Event System).

Reference [21] models the behavior of systems Using a modular approach where the global system is logically divided into smaller modules, which can be efficiently verified. Confidentiality properties verified flow of physical information may allow an observer to infer about possible cybernetic actions. For example, the operation of a wind turbine depends on its physical size, wind speed, etc. and these properties can reveal themselves about the cybernetic features of the system.

The work proposed by [22] models the plant model with ODE equation to model the plant , this models are deterministic but the global models is not. This model is considering by the authors, strongly affected by the timing.

The development team of [23], this team tries to solve the problem of plant model inference based on execution traces. We consider a system consisting of a plant and a controller which interact in a cyclic way: on each cycle the controller first reads data from plant sensors (plant outputs) and then sends commands (inputs) to the plant. Was a case study is consider an elevator moving between three floors. Its simulation model is implemented using IEC 6149 function blocks in the NxtStudio [24].

The paper for [17] the closed-loop CPS modelling the consider models for both the plant and the control unit, and then the combined model is exposed to model-checking tool. Is used NuSMV tool [18] for their model checking analyses and convert the XML Function Blocks using an automatic technique to NuSMV language. Considering the plant model in this paper is proposed a model for a automatic cylinder with to actuates in Timed Automata Figure 5.
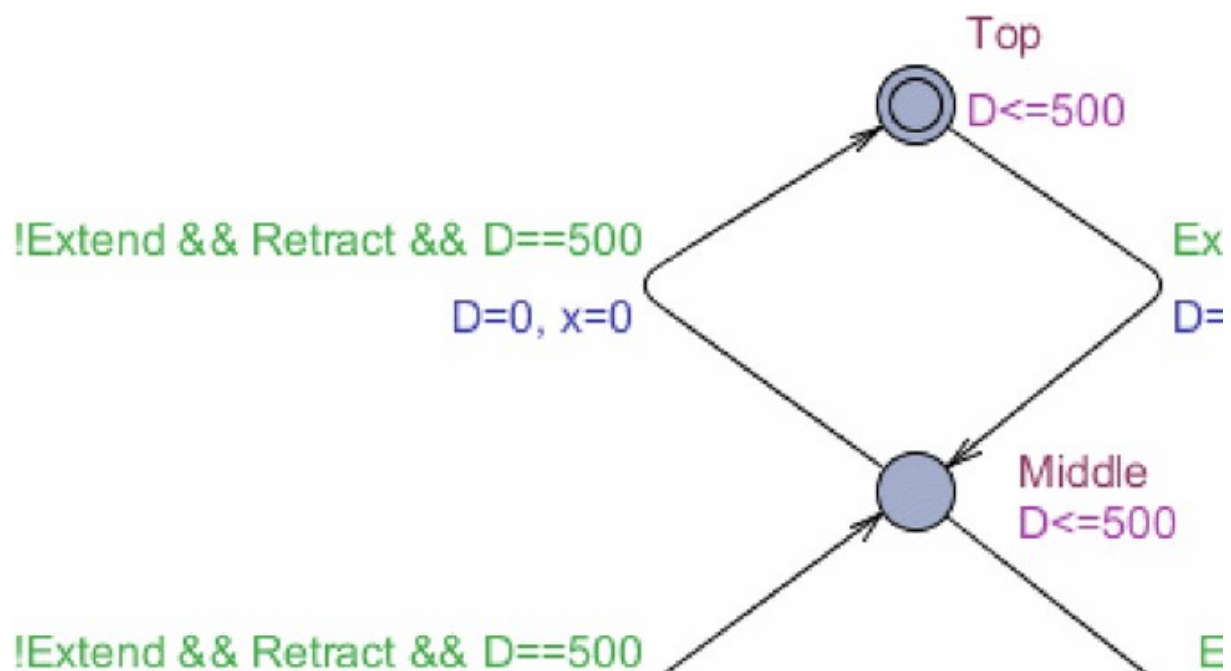
Figure 5. Timed automata model of a vertical cylinder with two actuates.

The used the same concept of time delay to create a NuSMV model considering time representation. Making used of the mechatronic modularity of the machines the propose a global model of a FESTO MPS-500 Processing station model. The station plant consists of: workpiece table with motor, drill module, tester and holder cylinders. The papers also show same results of analysing the global solution and the importance of correctly modelling the plant model.

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2.2. Plant modelling considering Continuous-Time approach
The work proposed by Lee [22] models the plant model with ODE equations; those models are deterministic but the global model is not. Authors consider that the obtained model is strongly affected by considering time modelling.

In the paper proposed by Malik and his team [23] it is considered the continuous dynamics of the plant using HIOA (Hybrid I/O automata) [24]. It is proposed a model of a train and his respective gate, that has a discrete and continuous behaviour and is, usually, used to model components such as computers that have discrete behaviour but continuous impact in the real live. The controller initiates the discrete location switches and in each location the plant exhibits different dynamics. HIOAs are then discretized to named as SHIOAs. Each SHIOA is transformed into a basic function block, while a network of such SHIOAs are transformed into a composite function block. The resulting plant composite function block is then joined with a controller designed in IEC-61499 (or some other PLC programming language) to perform controller testing and validation within a single framework. A case study is used for illustration, and the technique is considered validated.

The work proposed by Pohlmann et al [25] uses a combined approach that uses MechatronicUML [26] and Modelica [27], taking in consideration using ModelicaML [29] formalism. It is proposed a Modelica library [28] for modelling communication under hard real-time constraints that is based on the work already done in MechatronicUML environment. This method only considers the plant models in the simulations performed in Modelica and only tests the respective controller.

The Ishigooka team [30], [31] proposes a technique of construction of a plant model simplification framework to support the plant model simplification, which reduces the computation load by domain-knowledge-based replacement of complex model components and approximation of the model behaviour by model parameter configuration based on feedback of simulation results considering a plant in continuous domain (Figure 6). The plant in this approach is described by using differential-algebraic system of equations, and this approach tries to simplify by giving same values to same parameters.
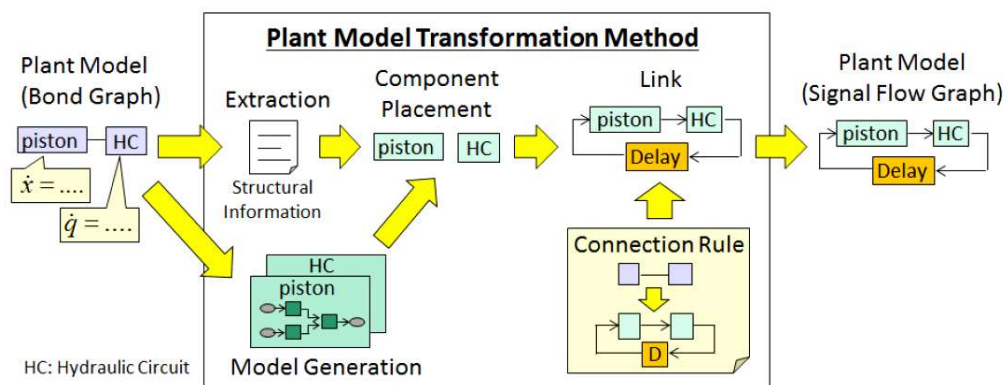

Figure 6. An overview of simplification approach using an example of sophisticated plant model [30].

In fact, this approach uses the results of simulation to create simplified models to use in the verification process. This is performed by reduction the detail in same aspects that was no importance to the testing process.

3. Research directions

In the domain of CPS and Internet of Things (IoT) there is still a huge gap in several areas, as presented in [5] and [6], such as: sensing , communication, computing, cognition and autonomous control. Figure 7 illustrates the main areas that must be explored in the context of CPS domain.
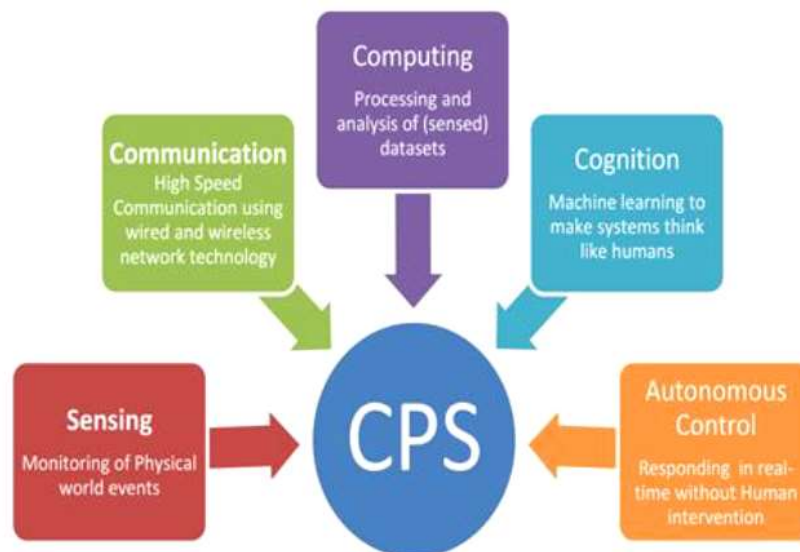

Figure 7. Areas of research in CPS domain.

Research into domain of cyber-physical systems is still in its infancy so there is still a long way to explore. There are many areas to be considered to ensure the symbiosis from the cyber and physical parts of a CPS. In near future, the core research will focus on three main points:

- How to ensure the dependability of cyber-physical systems algorithms / programs? It is imperative this point. Critical real-time response systems, which are the case for CPS, should be carefully analysed and combined with methods to ensure that they truly are reliable.
- How to solve problems of CPS modelling taking into account all necessary aspects, in order to assure correct communication between different equipments and how to extract the correct information during systems' functioning?

In this context authors will focus on exploring and studying the fidelity of co-models, developing methods and guidance on how to build co-models of systems that sufficiently predict their behavior. In particular, it will be considered the level of abstraction, granularity and time computation required to predict the behavior of the modeled system and to demonstrate that evidence gathered from the model is applicable to the real system that is built. Modelling aspects related to networked real-time control, and, in particular, for modeling physical plant will be considered, considering both expected behavior and possible failures.

4. Conclusions

CPS and IoT in the context of Industry 4.0 are some concepts that research is focused for solving some scientific and technological challenges related, mainly, with following areas: sensing, communication, computing, cognition and autonomous control. Authors of this paper are focused in three main aspects concerning dependability of CPS with distributed controllers, mainly on the domain of correct modelling of those systems, in order to obtain a correct specification for the respective controllers. For this purpose, modelling techniques and computation times for simulations and verifications are key aspects.

Continuous time and discrete-event time models are being created, and techniques for using them are being developed, in order to facilitate designers' tasks on obtaining a correct specification for CPS with distributed controllers. Also, plant and controller's interaction, as well as the study of communication standards of industrial controllers, such as IEC 61850, are being carefully studied.

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