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# Cyber-physical platform development and implementation for industry 4.0

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## ABSTRACT

Industry 4.0 is referred as the fourth industrial revolution that represents the information intensive transformation of industrial automation and manufacturing processes. Cyber-physical systems (CPS) are building blocks in Industry 4.0 and part of the Industry 4.0 vision. This paper presents a cyber-physical platform development and implementation strategy for Industry 4.0 applications. It has been considered a cyber-physical platform model (CPP) built upon hardware reconfigurable technology based on a Field Programmable Gate Array (FPGA) processor framework. The development strategy exploits the full benefits enabled by reconfigurable hardware, such as scalability of complex systems, platform-based design approach, adaptive processing, real-time constraints management, or high performance prototyping capabilities. The implemented experimental setup also combines major advantages of both the hardware and software platform-based design trends in Industry 4.0. In this endeavor, the used software toolkit comprises the entire system complexity as a high performance integration layer. The presented design method and implementation strategy can serve as rough orientation for future CPS research and development activities.

## KEYWORDS

industry 4.0, cyber-physical system, reconfigurable hardware technology, FPGA processor, software platform

## 1. INTRODUCTION

According to a general rule definition, Industry 4.0 includes cyber-physical systems (CPS), cloud computing, the internet of things, and cognitive computing, by creating the so called “smart factory” entities. Industry 4.0 is a vision and journey conceived as the next stage of organization and control of the production and manufacturing cycle [1]. Their autonomy and decision tasks are transferred to individual automation systems and machines via powerful information system. In this way structured units implement a connected environment of data exchange, automation systems, manufacturing processes, services, and people. This environment represents the structural basis of smart industry.

CPSs are building blocks in Industry 4.0 that links digital technology and physical environment in an industrial context. They are combinations of intelligent physical components objects and systems representing a next stage in an evolution and ongoing improvement of functions integration. CPSs connected through networks are the enablers of the smart factory concept of Industry 4.0 [1, 2]. Additionally, they exhibit new capabilities in product design and development, diagnosis and monitoring of industrial processes, products prototyping, remote control and real-time applications, respectively in maintenance and user-friendly services. In this way CPSs enable industrial systems able to communicate and network them with highly improved manufacturing efficiency capabilities. CPSs monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. By using the framework of internet of things these systems cooperate and communicate with each other and with humans, respectively share information and data in real-time both internally and across managing services. Moreover, they also include smart analytics

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properties, self-configuration abilities, or dimensions of simulation and twin models. Shortly expressed, CPSs basic characteristics and behaviors may be enumerated as follows [1, 3]:

- they are building blocks of Industry 4.0 enabling a large set of additional high performance manufacturing capabilities;
- CPSs can be uniquely identified by using Internet Technology (via individual IP address);
- they embed electro-mechanical actuators, electronics, intelligent sensors, digital microelectronics, information technology, microprocessor-based controllers, artificial intelligence, cognitive abilities, and network operation capabilities;
- they represent the next evolution stage in manufacturing and engineering bridging of digital technology with physical environment (in other words converge information technology and operational technology);
- they have embedded intelligent control systems that enable high performance communication in complex network systems.

All the above listed behaviors contribute to implementation of the challenging smart factory concept and smart logistics in Industry 4.0.

## 2. CYBER-PHYSICAL SYSTEM BASICS

CPS research and development represents an emerging research topic with high potential impact both on human society and modern industry. Generally speaking, CPSs are referred as the next generation of engineered systems that integrate knowledge and information technologies into physical objects. In other words, they are considered as the highest level of integration of physical, embedded hardware, and information technology systems [1, 2]. Therefore, the main CPS concept is based on integration of computation with physical processes bridging various high level technologies and engineering domains. In this approach the word “physical” means all the physical objects used in nowadays industry, such as physical plants or smart factory units that embed electrical actuators, a large scale of intelligent sensors, electrical motors, power electronic converters, mechanical ensembles, and so on. They all together are commonly referred as the “physical world” or “physical plant.” The “cyber” word there means the trans-disciplinary field of communication, computing, and control. In fact cyber implies the highest level integration of computation, communication (also including data storage), and control technologies (also including monitoring and sensing). Cyber and physical systems tightly integrated at all scales and levels represent the next generation engineering with currently an invaluable impact on society and economy [2, 3].

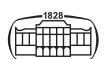
However, being still a very young research field does not express sufficiently crystallized theoretical basics yet in international references. Therefore, it is quite difficult to

evidence a well established model widely accepted in the related scientific literature and used at a large scale as support for CPSs development and implementation. What is almost commonly mentioned in papers and presentations is the bounding of the cyber and physical world via their main modules and communication links, as shown in the block diagram from Fig. 1.

Due to their extreme complexity high performance CPSs design is a difficult engineering undertaking. This challenge originates not only from their high complexity, but the cohabitation of analog and digital hardware, utilization of very different software technologies, as well as the existence of both analog and digital signals inside the system. Not at least, CPSs are a confluence of cutting edge last generation technological streams that should be properly integrated and managed during the entire development process.

Obviously, the development and implementation of a modern CPS claims a multidisciplinary design methodology [4]. Additionally, a model-based approach that may significantly unburden the whole design efforts invested is also recommended. From this point of view deterministic models that include differential equation systems, clear mathematical models, well defined software algorithms, modularized program tasks or synchronized digital circuits looks to be very useful. Engineers widely use such models because of their capability to high level approximate, imitate, and reproduce physical processes. Of course, real world is full of uncertainty, but even in this case deterministic models are preferential for researchers involved in the topic. Hence, despite of their limitations and drawbacks such models still represent the most used framework in design and development processes. In international references nondeterministic models that are also used in CPS developments are often mentioned [4]. Nondeterministic and probabilistic models are useful and necessary to handle uncertainty or unknowable events or behaviors. They do not affect in negative sense the deterministic models.

However, CPS developers and researchers face several prominent challenges of the topic. Among these should be mentioned that the complexity of CPS demands new system models being able to faithfully reproduce events and processes both inside cyber- and physical space. New software simulation toolkits and design platforms are required in order to handle CPS complexity. Specific hardware integration platforms are also welcome to unbundle the hardware development efforts [4–6]. The above predetermines a new CPS approach that manages design complexity by creating abstraction layers in the design flow (for example: hardware platform, software platform). On the other side, progress in CPS research and development may be accomplished only by using the latest technologies being available on the market. The latest network and communication technologies, embedded systems, sensor technologies, control theories, or artificial intelligence technologies are also included. Additionally, intelligent control is needed not input reference signals for CPSs. Nevertheless, a paradigm shift is required that puts emphasis on the decentralized



control systems that exhibit self-configuration and reorganization abilities instead of the previously used centralized architectures.

### 3. RECONFIGURABLE HARDWARE BENEFITS IN CYBER-PHYSICAL SYSTEMS DEVELOPMENT

The reconfigurable hardware technology is considered as one of the most challenging design paradigms in modern digital systems development. Instead of the traditional approach of digital systems design this technology uses hardware description language (HDL) techniques incorporating a high level of abstraction. It means that the designs are created in a lexical format that describes the essence of the design in structural or functional form. This behavior looks extremely useful in case of CPSs development and implementation. As it has been shown in the previous paragraph, CPSs are in fact a sum of complex heterogeneous systems [7]. The design and implementation of the entire software layer suitable for safety and reliable control of such a complexity is a difficult engineering undertaking. Reconfigurable hardware technology implemented mostly in Field Programmable Gate Arrays (FPGAs) provides a convenient framework for software code design platforms. Thus, FPGAs enable dynamic configuration of algorithms, allow different implementation variants of the same function, provide algorithm's partitioning to split a

function, or performs on-chip distributed and parallel computing of program tasks [7, 8].

Another challenging issue regarding the CPSs implementation refers to the real-time constraints problem. The interaction of CPS with the environment inherently introduces several aspects linked to the time boundaries constraints inside the system. FPGAs possess the ability to reduce time scale constraints by using their parallelization and parallel computing behaviors, being ideally suited for distributed tasks solving or network computing applications. They also exploit the advantages of the fine-grained instruction level parallelism as well as coarse-grained functional parallelism. In this way the time boundaries constraints are managed with incomparably higher efficiency than in case of any other microprocessor-based digital systems. By allowing multi-grid computation, FPGAs are ideal platform for fine-grained parallel computing, representing the perfect solution with which to implement highly concurrent control offering the huge advantages of flexibility, adaptability, and ease of scale [8, 9]. This is another benefit of this technology against classical solutions.

Additionally, their immense computational efficiency is matched by rich on-chip interconnectivity and high bandwidth concurrent memory access, achieving huge re-routing abilities that abstract the implementation details [8, 9]. All the above mentioned behaviors predestinate FPGAs to be used in many applications as accelerators' platform. This can be achieved by building up custom hardware architecture that is suitable to provide real-time operation where imposed time

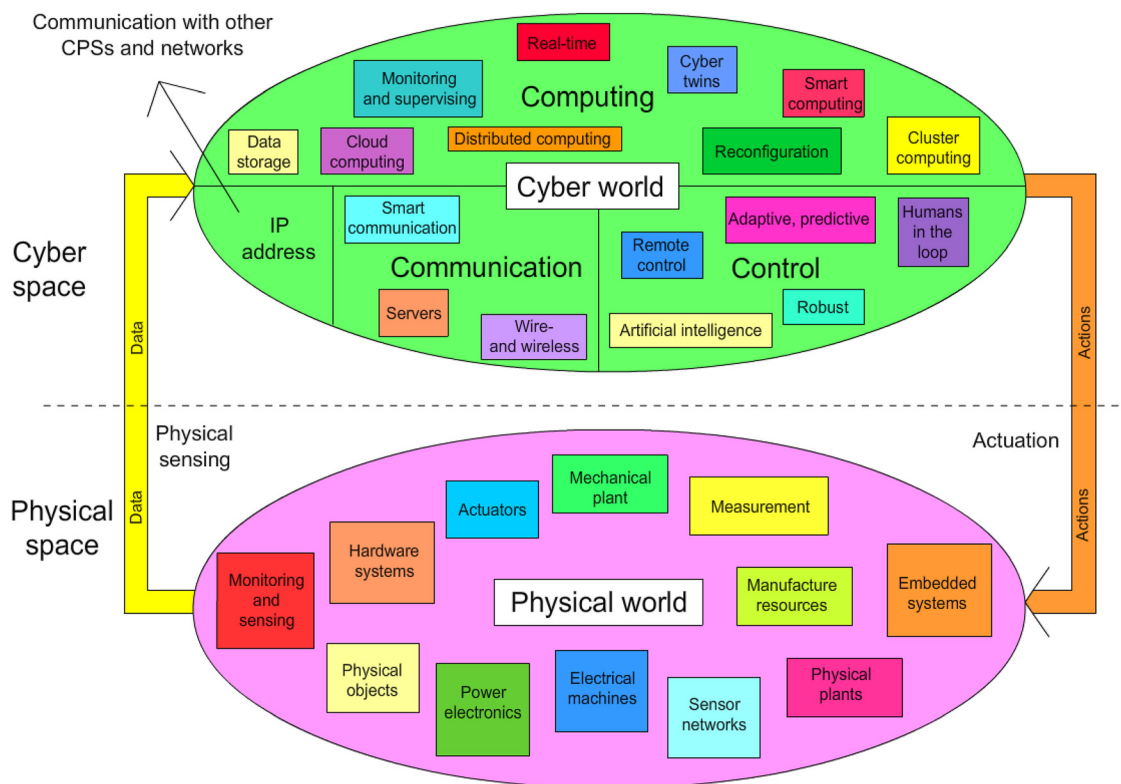


Figure 1. Cyber-physical system topology

constraints are complied. In other words the application is accelerated up to fit into given time scale intervals.

Scalability represents another benefit of hardware reconfigurable technology in CPSs development [7]. FPGA-based systems exhibit an outstanding versatility and flexibility during the development. They can be quickly reprogrammed to change functionalities, to access data, or to reconfigure its hardware structure. Therefore, FPGAs are very scalable on the microprocessor-based market. Last but not least, FPGAs are also remarked as powerful and versatile prototyping platforms. They offer the full possibilities to test various hardware architectures, to implement hard scheduling techniques, or to design novel hardware topologies.

#### 4. RECONFIGURABLE HARDWARE-BASED CPS MODEL

Considering the above mentioned theoretical remarks an original FPGA-based CPS model specially conceived to exploit the full benefits and advantages of reconfigurable hardware technology is proposed. For this reason, it is given the block diagram shown in Fig. 2.

The physical world of this CPS is based on a 3D manufacturing plant that embeds three stand-alone perfectly identical modular manufacturing cells. Each cell is able to generate a complex 1-axis mechanical motion. Together they cover the full 3D space on the x, y, and z axis. The motion quality and parameters are measured by adequate position and velocity sensors. At the same time, the 3D

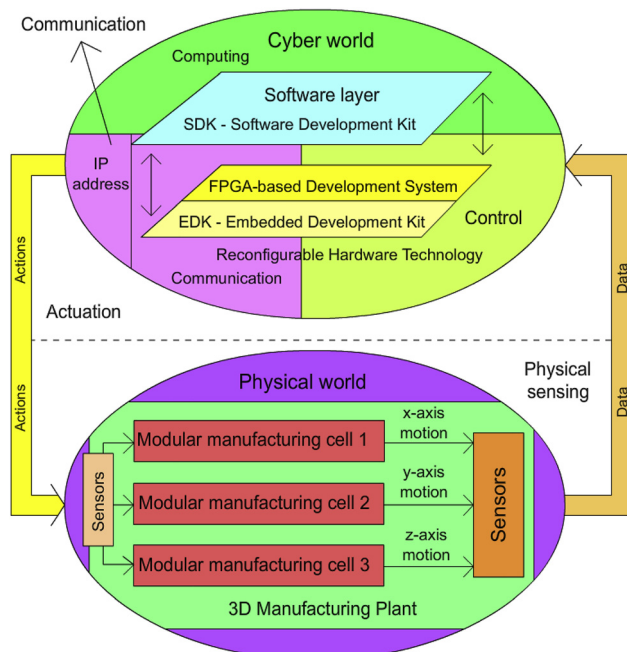


Figure 2. Reconfigurable hardware-based CPS model

manufacturing plant also receives external stimuli signals via adequate sensors networks (temperature sensors, humidity sensors, light intensity sensors, pressure sensors, etc.). The cyber space (or cyber world) performs its three major functions: computing, communication, and control. Its communication with other CPSs or networks is allowed via individual IP address. All the computing resources are implemented by using an Embedded Development Kit (EDK) software toolkit specially developed for reconfigurable hardware applications [10]. The program tasks and algorithms will be uploaded then into a FPGA-based development system (a ready-to-use manufacturer board). The control strategies are implemented on the software layer. This is a Software Development Kit (SDK) able to perform high level code synthesize operations, functional simulations, translate or map operations, time constraints simulation, or to generate bit-stream files that will be uploaded on the FPGA processor-based framework. In this way the manufacturing plant will form a high performance smart production entity well suited for a wide range of Industry 4.0 applications [11].

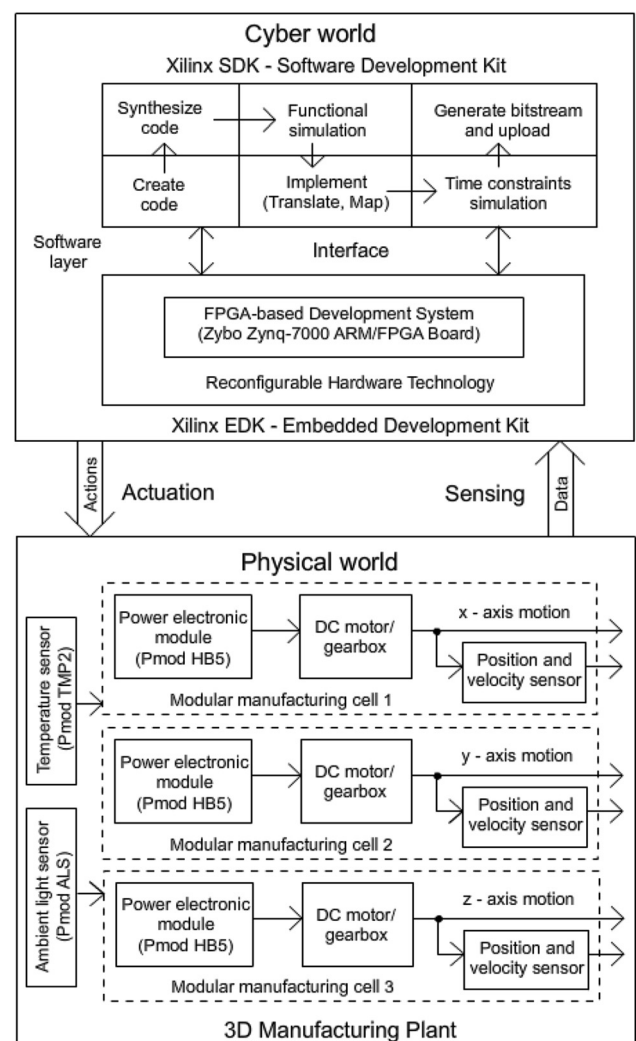


Figure 3. Detailed structure of the proposed CPS model



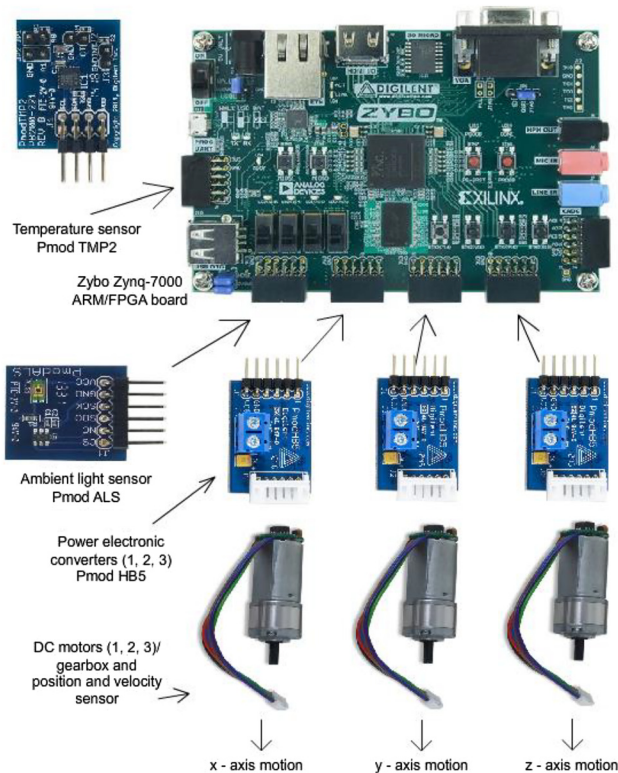


Figure 4. The hardware framework of the proposed CPS model

## 5. FPGA-BASED CYBER-PHYSICAL PLATFORM DEVELOPMENT AND IMPLEMENTATION

This paragraph presents how the reconfigurable technology-based CPS model introduced in Fig. 2 is expanded in detail and the full implementation steps of a (CPP) based on FPGA processor framework.

In this endeavor let us consider the block diagram from Fig. 3, with concrete specification of hardware and software components that are used. As it has been mentioned before, the physical world of the CPS is in fact a 3D manufacturing plant embedding three identical units. Each unit is composed by a power electronic module that drives a DC motor with built-in gearbox module. The motor also embeds a high performance position and velocity sensor that delivers precise information about the rotor angular position and angular speed. The manufacturing plant is able to receive information from its near surrounding environment, in this case about the ambient temperature and light intensity. As function of this information the CPS acts and executes operations according to a previously programmed algorithm in the cyber space. The main module of the digital hardware system is the Zybo Zynq-7000 ARM/FPGA development board that is a high performance FPGA processor-based ready-to-use manufacturer board [12]. Zybo is a feature-rich embedded software and digital circuit development platform built around the Xilinx Zynq-7000 family [12]. In detail, the

board integrates a dual-core ARM Cortex-A9 processor with a Xilinx 7-series FPGA circuit that is interfaced with a rich set of peripherals (Pmod-type modules, on-board memories, audio/video inputs/outputs). The hardware framework and interconnection topology (indicating all the interfaced ports) of the proposed CPS is plotted next in Fig. 4.

The Zybo Zynq-7000 system is interfaced with several ready-to-use modules. One is the compact and small PCB size ambient light sensor (*PmodALS*) that converts light to digital data with 8-bit resolution, the other is a 16-bit high accuracy temperature sensor (*PmodTMP2*) using the I<sup>2</sup>C communication protocol for data transmission [13]. They measure the light intensity and environment temperature and the CPS platform takes decisions as function of this information. The electromechanical actuators are three DC motor/gearbox (1:19 gear ration) units with rugged, heavy duty construction that include encoder for sensing rotation and speed [13]. These are interfaced to the Zybo Zynq-7000 system via compact *PmodHB5* modules that are 2A H-bridge converter units specially manufactured to drive small to medium sized DC motors with operating voltage up to 12V. All together forms three compact and modular one-axis manufacturing cells.

The cyber world has been developed upon a two-layer platform-based strategy [14]. According to this approach the complex structure and heterogeneity of the application should be exploited by an adequate platform that exploits the available intrinsic parallelism with the right granularity. Such platform will operate as a high level integrated design environment. In the first step of the cyber space development the Xilinx EDK system implemented under the Vivado Design Suite (VFS) has been used [15]. VDS represents a new approach for broadly deploying system platforms using next generation C/C++ and IP-based (Intellectual Property) high productivity design. Such technology allows reduced design and implementation cycles, short analysis and verification convergence. Starting and deploying a new project in the *Vivado HLX Edition* toolkit results the general block diagram printed in Fig. 5.

The general block diagram of the CPS hardware platform is shown. The main module of this platform is the FPGA processor-based ZYNQ processing unit interfaced to the system via the AXI Interconnect unit. This allows special bus configurations being able to fully control the rest of peripherals and sensor modules. The standard devices that have been interfaced to the system are the *PmodGPIOs* switches and LEDs (4 switches and 4 LEDs). Three stand-alone 6-bit *Pmod* ports are allowed to the *PmodHB5* bridges interconnection and other two for the *PmodALS* light sensor, respectively the *PmodTMP2* temperature sensor. This sensor technology allows rapid generation of the hardware platform connectivity design along with the necessary software stack being dramatically shortened all the design and verification times. The entire development flow provide for a high level of synthesis and analysis of complex HDL designs, rapid configuration, separation of platform development and differentiated logic. It is important to

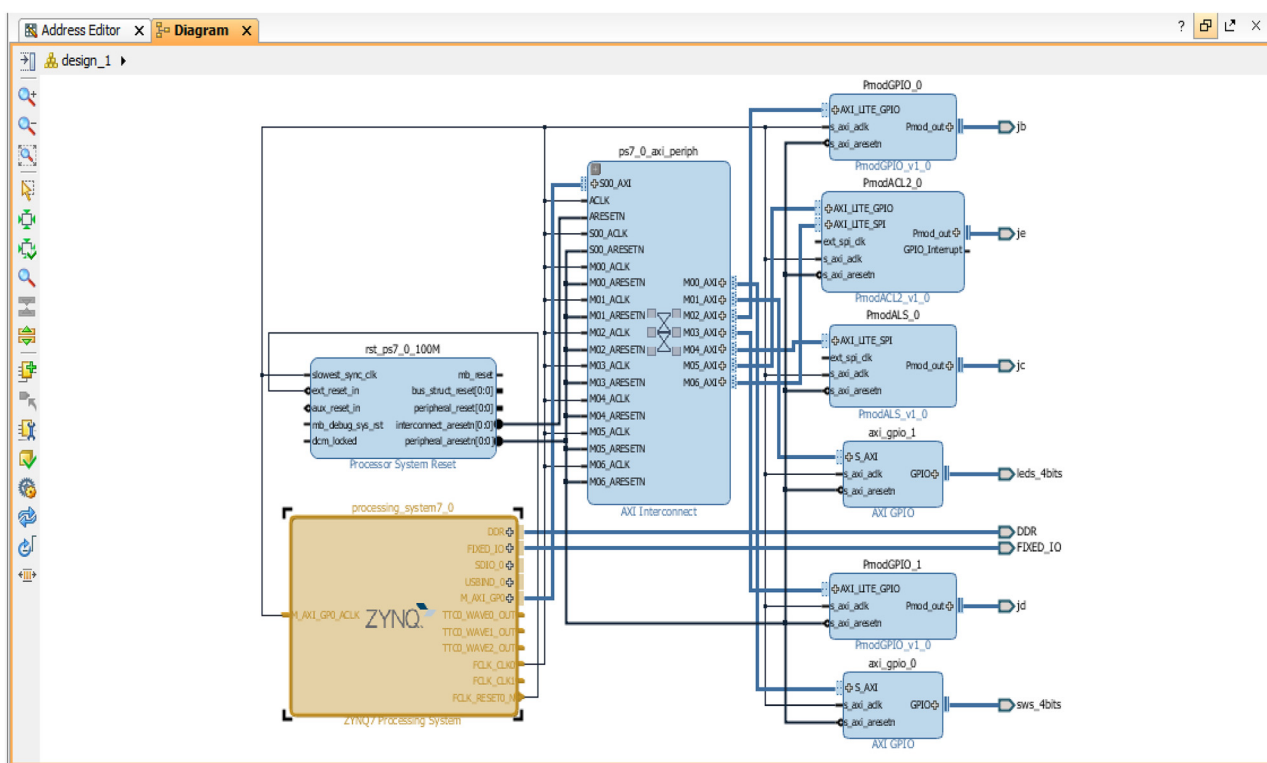


Figure 5. The interface modules connection to the Zybo Zinq-7000 development board

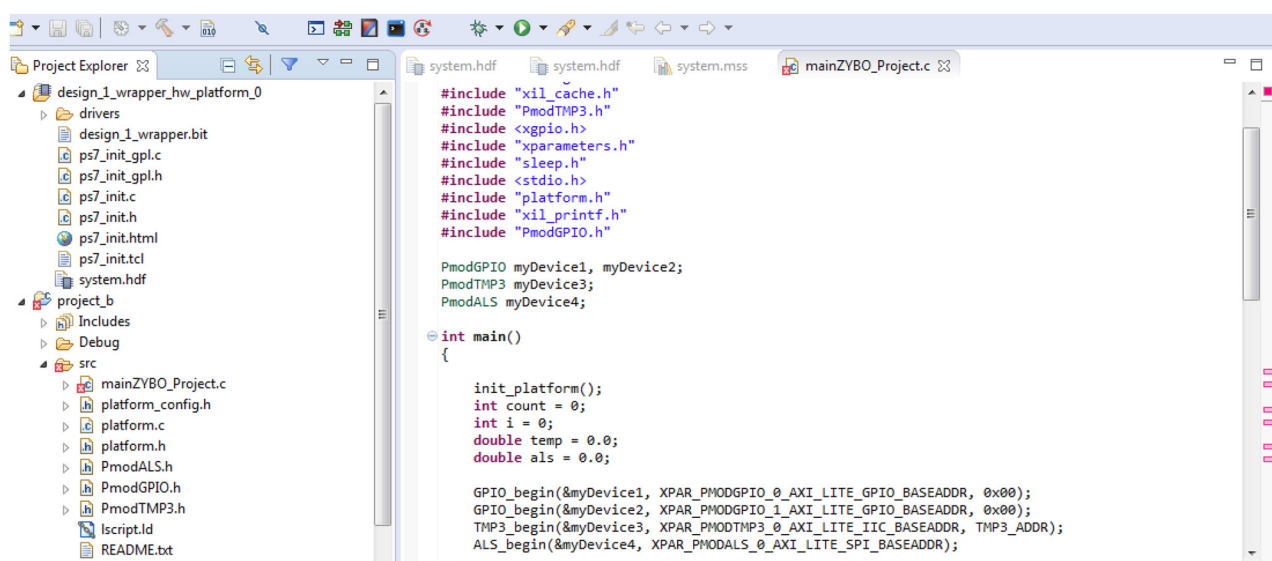


Figure 6. The software platform implemented in Xilinx SDK and the main program C source code

remark the efficiency and high flexibility of the implemented digital structure.

The hardware platform implementation mandatory is followed by the software layer development of the CPS. For this purpose the Xilinx SDK toolkit is used enabling C/C++ source codes to be directly synthesized into VHDL. This is a complex software platform that allows user tailored design via a set of well defined steps and programming operations.

At the beginning some input data must be specified that covers information about specification of the platform, timing constraints, or application and mapping instances. Then follow the source code development. During the synthesis processes flow the input specifications are converted into an FPGA implementation. This operation embeds five main steps: Model parsing, Component initiation, Component connection, Top-level VHDL file creation, and Switch

configuration. All these design and implementation steps under the Xilinx SDK toolkit are shown next in Fig. 6.

On this plot under the driver modules are listed all the required C source code files that make up the integrated software platform. A piece of the main C program source code for the CPS control is also shown. As is possible to observe, *Vivado HLX* highly accelerates the entire design and development implementation of the CPS by enabling C/C++ source codes to be directly synthesized into VHDL. Therefore it is considered as a rapid IP integrator from C language to silicon technology that generates highly efficient software for CPS developments and implementations.

## 6. CONCLUSIONS

The paper proposes an original FPGA-based CPS model conceived to exploit the full benefits and advantages of reconfigurable hardware technology. This model has been specially targeted and developed for Industry 4.0 applications that widely embed cyber-physical building blocks inside their internal structure. The implemented laboratory setup combines major advantages of both the hardware and software platform-based development approach. In this way the entire system complexity is comprised as a high performance integration layer. The unfolded design method and implementation strategy can serve as rough orientation for future CPS research and development activities.

## REFERENCES

- [1] <https://www.i-scoop.eu/industry-4-0/>.
- [2] K. D. Kim and P. R. Kumar, "An overview and some challenges in cyber-physical systems," *J. Indian Inst. Sci.*, vol. 93, no. 3, pp. 341–352, 2013.
- [3] <https://www.cs.purdue.edu/homes/bb/CPSReviewPaper.pdf>.
- [4] A. Lee, "The past, present and future of cyber-physical systems: A focus on models," *Sensor. J.*, vol. 15, no. 3, 2015. <https://doi.org/10.3390/s150304837>. PMID: 25730486.
- [5] Y. Li, T. Callahan, E. Darnell, R. Harr, U. Kurkure, and J. Stockwood, "Hardware-software co-design of embedded reconfigurable architectures," in *Proc. 37th Annu. Design Aut. Conf.*, ACM, 2000, pp. 507–512.
- [6] J. Becker, M. Hubner, G. Hettich, R. Constapel, J. Eisenmann, and J. Luka, "Dynamic and partial FPGA exploitation," *Proc. IEEE*, vol. 95, no. 2, pp. 438–452, 2007.
- [7] T. Grimm, B. Jansen, O. Navarro, and M. Hubner, "The value of FPGAs as reconfigurable hardware enabling cyber-physical systems," in *20th IEEE Conf. Emerg. Technol. Factory Aut.*, 2015. <https://doi.org/10.1109/ETFA.2015.7301496>. INSPEC: 15555921.
- [8] G. Husi, Cs. Szász, and H. Hashimoto, "Application of reconfigurable hardware technology in the development and implementation of building automation systems," *J. Environ. Eng. Manag.*, vol. 13, no. 11, 2014. ISSN: 1582-9596. <http://omicron.ch.tuiasi/EEMJ>.
- [9] N. Rink and J. Castrillon, "Trading fault tolerance for performance in AN encoding," in *Proceedings of the Computing Frontiers Conference*, 2017, pp. 183–190. ACM New York. <https://doi.org/10.1145/3075564.3075565>.
- [10] <https://www.xilinx.com/support/documentation-navigation/development-tools/mature-products/embedded-development-kit.html>.
- [11] [https://www.xilinx.com/support/documentation/sw\\_manuals/xilinx2015\\_1/SDK\\_Doc/index.html](https://www.xilinx.com/support/documentation/sw_manuals/xilinx2015_1/SDK_Doc/index.html).
- [12] <https://store.digilentinc.com/zybo-zynq-7000-arm-fpga-soc-trainer-board/>.
- [13] <https://store.digilentinc.com/pmod-modules/?sort=bestselling&page=2>.
- [14] Cs. Szász, "Last generation mechatronics: a two-level platform-based reconfigurable technology approach," *EEMC'18 Int. Conf. Publ. Recent Innovat. Mechatron. J.*, vol. 5, no. 1, 2018. <https://doi.org/10.17667/riim.2018.1/6,2018>.
- [15] <https://www.xilinx.com/products/design-tools/vivado.html>.

