Recent Innovations in Mechatronics (RIiM) Vol 7. (2020) No 1.
DOI: 10.17667/riim.2020.1/1.

Intelligent Buildings as Cyber-Physical Systems: a Reconfigurable Hardware Technology-based Approach

SZÁSZ Csaba
Technical University of Cluj, Department of Electrical Machines and Drives
Csaba.Szasz@emd.utcluj.ro

Abstract – **This paper discusses idea to change the way to approach intelligent buildings (IBs) development and implementation by taking into account last evolutions in cyber-physical systems (CPSs). Therefore, the main goal is to extend IBs design engineering with the constraints of systems in a CPS context. As well known, smart buildings are increasingly complex as they integrate many scientific areas and research topics, as well as a large scale of last-generation technologies. At the same time, the Internet has deeply transformed the way to manage information and services, respectively how information is transmitted and computed in the cyber space. The quick management and information processing inside cyber layer challenges the interaction with the physical world in a sense to develop IBs as smart distributed systems or CPSs. In addition to this, the paper emphasize the original idea of developing reconfigurable hardware technology-based (RHT-based) CPS architectures for IBs implementation purposes. Benefits of the RHT application in a CPS context for IBs are widely discussed and analyzed. The unfolded theoretical background has been supported by an implementation example using Vivado Design Suite HLS software technology. These experiments evidence the advantages and versatility of this challenging implementation paradigm of latest digital technology, applied for current-state IBs development.**

Keywords: *intelligent building, cyber-physical system, reconfigurable hardware technology, FPGA processor, software platform.*

I. Current state in Intelligent buildings development

It is well known that with the continuously increasing human standards of life a greater demand for more comfortable, operationally efficient, safe and energy efficient living places - called generically "intelligent houses" is expressed [1]. Of course, nowadays the IB term becomes generally consecrated and all the commercial or residential building tends to be designed by following the IBs concept and development paradigm. Therefore, is no doubt, in the next decades this goal will dominate all the evolutions, research efforts and achievements referred to this high interest and challenging topic of IBs [2, 3].

Of course, there is not enough room to discuss theoretical aspects related to the worldwide used definitions of the IBs concept or other interpretation issues. However, a plenty of international scientific references are especially dedicated to discuss theoretical issues related to this challenging topic and to offer viable solutions linked to modern IBs development and implementation [4, 5, 6, 7]. The main goal of this paper is rather to evidence the incredibly complexity achieved by latest IB topologies and structures and to emphasize that nowadays their design and implementation shifts toward into a full CPS context. Respectively, proposes an original RHT-based point of view aimed to unburden the sophisticated hardware and software design processes of a complex smart building architecture. In this endeavor latest RHT-based development systems will be configured and used. These hardware architectures will be supported by last generation software technologies that make possible versatile embedded design control systems implementation and development in IBs. Of course, before looks welcome to discuss and identify some current state IB structures or topologies, common trends regarding their future development strategies, respectively the impact of shifting IBs design engineering with the constraints of systems in a CPS context.

Staring from the above remarks, fits here the important observation that from the users (or inhabitants) point of view current state smart buildings should fulfill several important criteria regarding their utility, efficiency and vocation. For example, a modern building should become a locus that ensures high level satisfaction and convenience for the peoples working or living in them. At the same time, an IB is a communication hub that receives and transmits a large scale of information with high speed and efficiency. Ensures network communication abilities through that provide high level economical and social care services. Smart buildings also should provide efficient management of its fossil- and renewable energy resources in a grid operation context. Towards, may be able to generate fast, flexible and economically efficient responses for its surrounding fast change economical and sociological environments. An IB may cohabitate and accommodates to severe climate changes and should provide the highest level of safety and security for its inhabitants. Not least, a modern building provides the highest level of human-related services in terms of healthcare, comfort-convenience, or life standard.

DOI: 10.17667/riim.2020.1/1.

Whatever, it is not difficult to deduce from the above ranked theoretical considerations that a current-state IB development strategy should cover at least three important criteria as is expressed next in Fig 1.

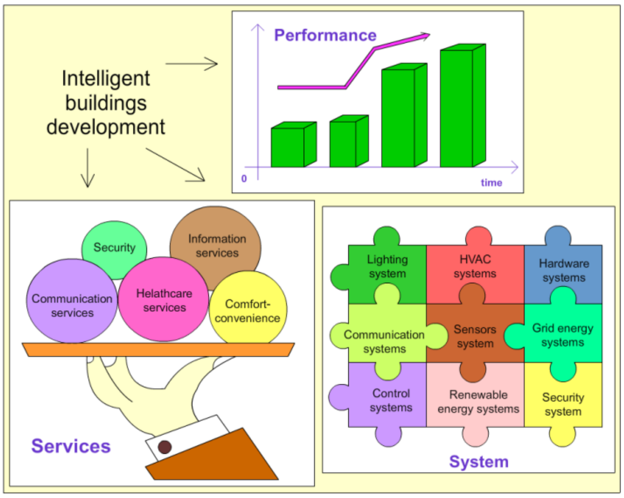

Figure 1 – Current-state IBs development criteria

In this approach these are the *Performance criteria*, the *System-based operation* and the *Services-based operation* of the considered IB. The performance-based requirement is related to the building performances and demands rather than used automation technologies and software systems provided. This expresses that the building inhabitants or occupants expresses more and more requirements according to their increasing life standards. The system-based approach covers all the technological issues that the IB includes, such as: HVAC (Heating, Ventilation and Air-conditioning) systems, grid- and renewable energy systems, network communication systems, security systems, control and processing systems, sensor and automation systems, and so one. The service-based criteria focus mainly upon the quality of services delivered by the considered building. Such services may be related to healthcare issues, communication and information services, security services provided, or other human comfort- and convenience linked services. These all together ensure a wide range of high quality, intelligent and user-friendly human life style activities [5, 8, 9].

On the other side there is the imminent question of what kind of development and implementation strategy should be followed in order to reach the above stated three important criteria of a current-state IB? How may be achieved all these demanding user-related requirements? Of course, there probably exists worldwide different types of approaches and implementation strategies. Without the claim to enter here in detailed international literature analysis, there is mentioned one that has been unfolded in details in reference [8]. According to this, a modern intelligent building development may become successful if is taken care four important aspects, or concepts: the inhabitant needs, the information technology requirements, the energy management and the adaptation behavior. All these have been covered under the so abbreviated IIEA model [8]. In a few words there the *Inhabitant* issue means that the building's owner or inhabitant is in the center of all developments that has been done. Consequently, all these serve its full convenience and life style comfort. The *Energy* concept is related to the idea that a current-state IB should operate both connected to conventional energy grids, as well as to full operate off-grid by using renewable energy resources. Of course, the impact of the internet and last generation information technologies is already so powerful that an IB also may fulfill the full role of an *Information* center (node) or hub. It is not difficult to accept that in such a situation cannot be omitted the concept of *Adaptation*, since all technological and information management issues, respectively human life standard requirements are under a fast evolving process. Therefore, results that the IB whole infrastructure should be able to adapt and accommodate to a large scale of external challenges. It means that fast and flexible well planned responses may be generated to the continuously changing external environment [8]. These all issues are briefly evidenced in the IBs development strategy presented in Fig. 2.

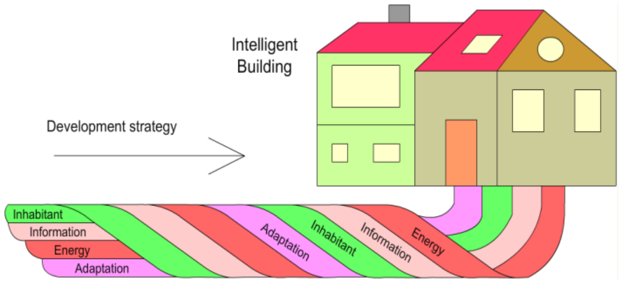

Figure 2 – Concept for current-state IBs development

It is also well known that a smart building structure is extremely sophisticated by integrating many scientific areas and engineering topics. Therefore, inside IBs structure nowadays cohabitates a large scale of different type control and communication systems, such as: electrical systems, electromechanical systems, hydro-pneumatic systems, electronic systems, mechatronic systems, microelectronic systems, sensor network systems, telecommunication systems, computer networks, remote control systems, or various type software and data processing systems. In addition, all these have been built on by using last generation hardware or software technologies with very different energy-level analog, digital, or other mixed (hydraulic, pneumatic, etc.) signals. To integrate all these subsystems in a coherent, safety and economical operating whole system that will represent the IB main smart architecture looks a really difficult engineering undertaking. On the other side, to decide where should be integrated or categorized each one from the above ranked system components into the four pylons (*Inhabitant*, *Information*, *Energy* and *Adaptation*) looks another cumbersome engineering task. After all, there is no yet a worldwide accepted IB model (architecture or structure) that may be considered generally adopted by a large number of researchers or development engineers involved in the topic. Hence, there are a plenty of related approaches in the international scientific literature.

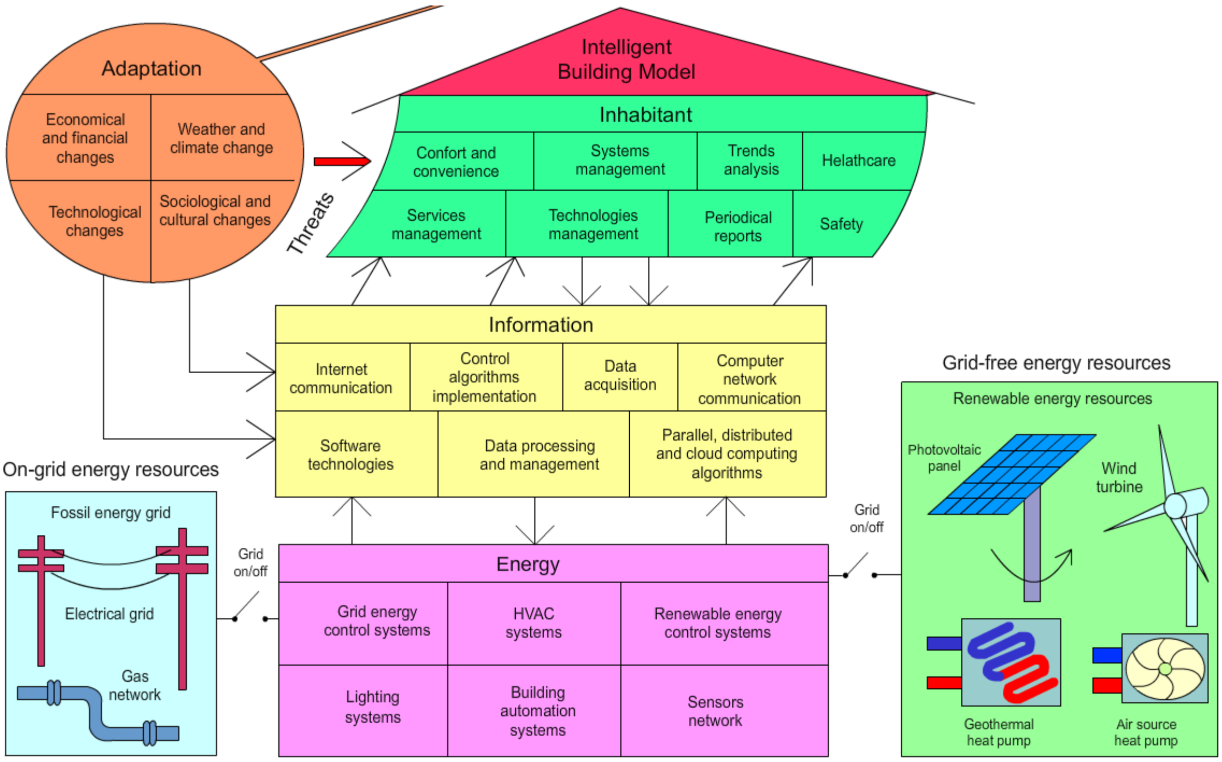

Figure 3 – Concept for current-state IBs development

In spite of all these, the identification of a generalized model that may be large-scale accepted by a wide range of researchers and fulfills the expectations of most demanding IB developers may be a welcome endeavor. For this reason, in Fig. 3 is proposed a block diagram which tries to comprise together all the most important and relevant component subsystems of a current-state IB. This concept also outlines the main issues that should be considered by all means for a modern IB development and implementation process. Of course, from the inhabitant's point of view it is important to be ensured the IB proper operation connected to the renewable energy resources as photovoltaic panels, wind turbines, and geothermal- or air-source heat pumps, as well as to the classical on-grid energy supply systems (as gas or electrical network) if necessary. All these energy resources fulfill the HVAC (Heating, Ventilation and Air Conditioning) and lighting necessities of the considered building, respectively ensures the adequate energy supply level to all the sensors, computers, actuators and building automation systems that operates inside them. Over the above marked *Energy* layer also should be considered a separate *Information* layer. This mandatory includes all the control, processing and communication tasks that takes place in a modern IB. There are considered the whole internet communication, data acquisition from the sensor network, computer network communication, parallel, distributed, or cloud computing algorithms execution, process control algorithms implementation, or other data processing, storage and management tasks. The full support for all these is provided by last generation software technologies. Obviously, in the center of all developments is the user or inhabitant of the building. The inhabitant requires safety, comfort, convenience, or simply formulated high-level life standard. This also includes a wide range of services, such as healthcare, safety, periodical reports reading and analysis, continuous information and so one. At the same time, for all these the inhabitant should perform some periodical systems management and technological management in order to keep the proper operational state of the full IBs hardware and software infrastructure. In addition, may take care about the external "threats" that inherently influences the entire buildings operation, such as economical and financial changes, sociological and cultural changes, weather or climate changes, or the very fast technological evolutions. Is not a question that these above requires important *Adaptation* skills of the IB model in order to be able to maintain its full operation state between the imposed reference levels.

II. INTELLIGENT BUILDINGS IN A CYBER-PHYSICAL SYSTEM CONTEXT

A short overview of the IB model proposed in the previous paragraph inherently lead to the general conclusion that a current-state IB structure is extremely complex and sophisticated. There are a high number of diverse components, devices and subsystems that should operate safety and efficient inside a functionally coherent working complex system. Towards, it is quite difficult to deal with heterogeneity of all these components and to embed it in intelligent manner into an unpredictable physical world under a continuous changing environment. Not at least all those elements express a cutting-edge last generation technological streams difficult to properly integrate and manage during the whole IB development and implementation process.

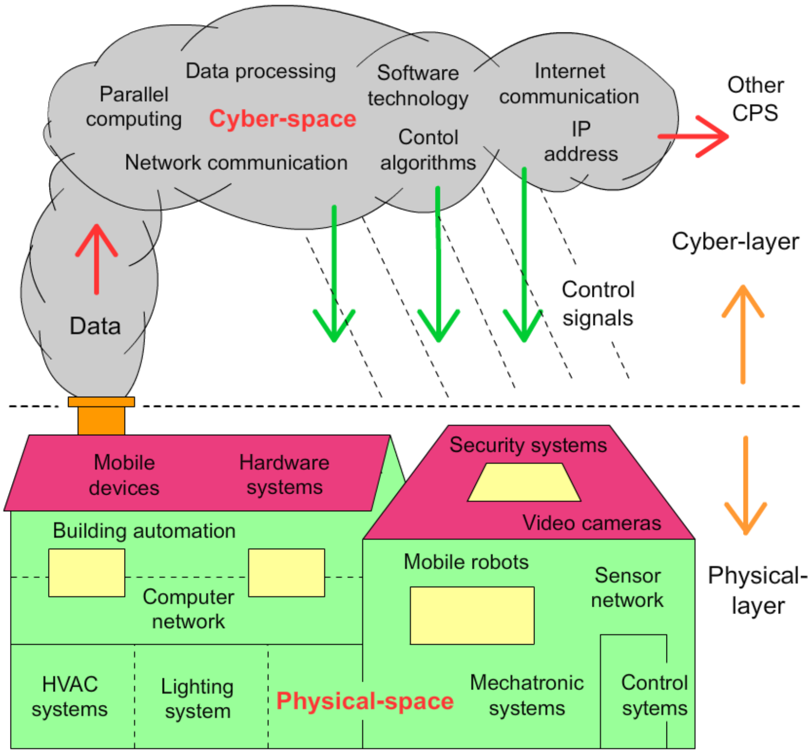

Figure 4 – Intelligent building development proposal in a cyber-physical system context

Fortunately, the unprecedented development of last-generation microelectronic technologies-based devices also has promoted the benefic trend of embedding more intelligence in physical objects. In other words, a lot of electronic devices and instruments become more "intelligent", exhibiting several additional features and behaviors as before. This trend leads then to the main idea of coupling devices each to other in order to maximize their operating efficiency. Therefore, heterogenic systems and components become able to interoperation and communication in network topologies. Step by step, such architectures tend to imitate complex cyber-physical systems (CPSs) structure and operation [9]. In fact, the CPS concept means the integration of intelligence and knowledge into physical object, by linking the physical world with information technologies. The result is the so called "intelligent object" as component part of intelligent production systems and manufacturing. By tight coupling computation with physical objects has born the CPS concept that embeds two main parts or layers: the "physical world" and the so called "cyber world". Obviously, the first refers to the considered physical plant or "physical layer", the second one being the trans-disciplinary field of computing, control and communication. These two layers integration at all scales and levels represents a basic component of the Industry 4.0 concept, as the next generation engineering trend.

However, it seems that the CPS concept widely used in industry can be also transposed easily to the smart buildings development and implementation area. In fact, to synchronize the operation of a high number of heterogeneous subsystems and intelligent devices that consists an IB structure the CPS-based approach looks one of the most adequate strategy. A similar approach is presented above in Fig. 4, where the full smart building development strategy has been placed into a CPS context. There may be delimitated clearly the two layers of the CPS: the physical and the cyber one. All the physical object, components, or subsystems are considered embedded into the physical space of the building. A huge amount of data is collected from this physical area and processed inside the cyber space. As final result of the computation processes and tasks will be generated control (or reference) signals back to the physical layer that will turn in concrete actions inside them. It is important to mention here that each CPS mandatory has its own IP address and should be able to communicate with other neighboring CPS structures. Towards, it is not without importance to outline here that the CPS-based approach is also well suited to solve other important issues as distributive operation, data scalability, interoperability, or security. For example, a smart building being a strongly heterogeneous environment data may be acquired from very different sources and processed in a distributed manner in different processing units. Toward, there are also very different energy level analogue, numerical, or mixed signals that should be scaled and processed in very same digital units. The interoperability is another important issue in IBs, since various subsystems or electronic devices being from different manufacturers with different technologies uses very different communication protocols or interfaces. In spite of all these they should be interoperable and interchange data between each other. In order to achieve all these goals to place IBs development and implementation into a CPS-based context looks a welcome and recommended endeavor.

DOI: 10.17667/riim.2020.1/1.

III. CPS-BASED IBS: THE RECONFIGURABLE HARDWARE TECHNOLOGY IMPLEMENTATION PARADIGM

The RHT represents perhaps the most challenging implementation paradigm of modern digital systems. As representative components of this leading role technology the FPGA (Field Programmable Gate Array) processors play the key role in the most demanding reconfigurable computing strategies implementation. This role can be fulfilled easily thanks to their specific on-chip internal hardware structure based on the ability of rapidly change hardware architecture with different functionality according to various user needs (Fig. 5).

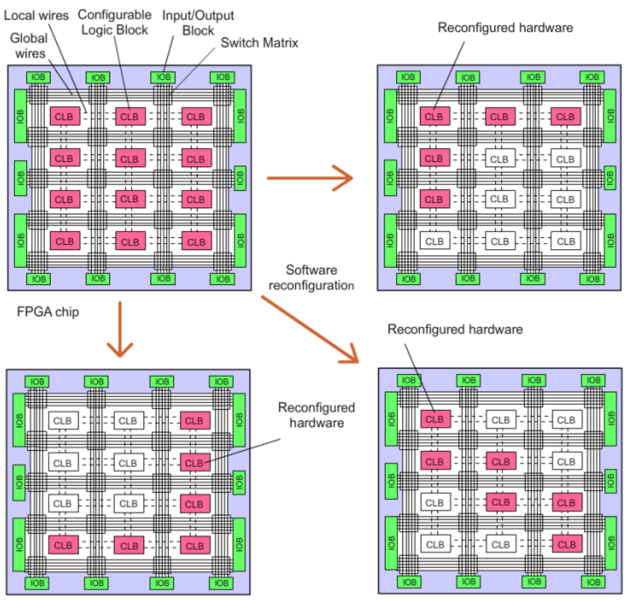

Figure 5 – The reconfigurable hardware implementation paradigm

This unique facility offered by the FPGA processors is facilitated via their fine-grained instruction level parallelism as well coarse-grained functional parallelism, by using custom computing technologies [9]. They are ideal platforms for fine-grained parallel computing, allows multi-grid processing, representing the best solution for concurrent tasks execution in control, monitoring, or communication applications. Additionally, FPGAs exhibits remarkable performances in distributed task solving or network computing [9]. Also exceeds in parallelization and parallel computing by rapidly changing its internal hardware structure and functionality, according to various user needs, as is expressed above in Fig. 5.

All these remarkable behaviors and facilities leads in a natural way to the idea presented next in Fig. 6. There is plotted a picture that outlines the outstanding versatility of reconfigurable hardware technology application in IBs development and implementation. According to this, a large scale of heterogeneous subsystems, components or electronic devices may be interfaced and controlled by the same FPGA-based development system. Each one of the smart building's components will allocate inside the FPGA chip its own distributed location that contains the necessary interfacing digital circuits on which hardware support runs their specific driver programs or tasks.

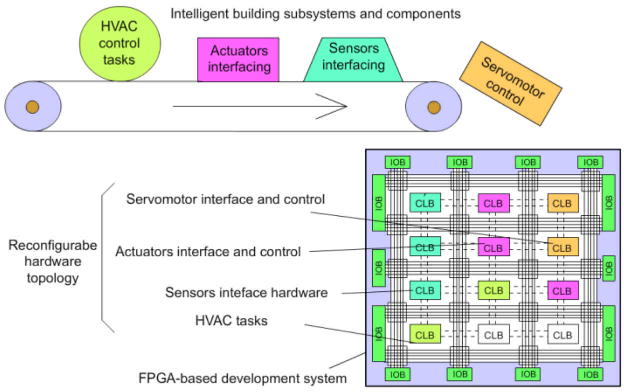

Figure 6 – The RHT application in IBs development and implementation

It is not difficult to observe that very different digital circuit topologies are parallel and distributed implemented on-chip and executes very different control algorithms or programs under the same FPGA's clock frequency. They occupy physically different locations inside the FPGA network architecture allocated by the implementation program. Of course, in specific cases also may remain unused hardware resources inside processor's physical array configuration. What is the most important the existing hardware resources can be allocated conveniently according to various user needs as function of applications complexity and software reconfigured if required as it is expressed in Fig. 5. This last behavior is an important issue in case of IBs development where - as has been mentioned before, very fast technological evolutions are unfolded in addition with several influences in a continuously changing external environment. For all these reasons the RHT implementation paradigm application emerges as a key strategy in this research topic. Shortly expressed, by using this technology implementation versatility and stability it can be maintained even under the pressure of a rapidly changing technological environment combined with more demanding user needs.

IV. THE RECONFIGURABLE HARDWARE TECHNOLOGY APPLICATION IN INTELLIGENT BUILDINGS DEVELOPMENT

In order to support the above expressed theoretical background let it consider a concrete RHT application example for IBs development under a CPS context. There is an arbitrary chosen IB topology that embeds several subsystems and components as follow: sensors for ambient temperature measuring with its interface circuits, servomotors and its interface modules for various motion control applications (doors and windows open, mechatronic systems control, household mobile agent's motion control, or HVAC valves actuation), and one ambient light sensor with its interface circuit. A full hardware system built upon FPGA-based RHT that is well suited for real-time control of such architecture is presented next in Fig. 7. This configuration nearly imitates the IB subsystems and components presented above in Fig. 6. For real-time implementation of this heterogeneous hardware topology has been used the Vivado Design Suite HLS software platform [10]. This is a toolkit produced by Xilinx Co. for synthesis, analysis and embedded implementation of hardware description language-based designs. In fact, this is a tightly integrated and scalable high-performance integrated design environment based on system-to-integrated circuits that synthesize at system level user defined IP (Intellectual Property) circuits with C-based algorithms [10]. In fact, by using Vivado, C language code is converted into programmable logic and results a state-of-the-art and comprehensive embedded development system based on RHT framework.

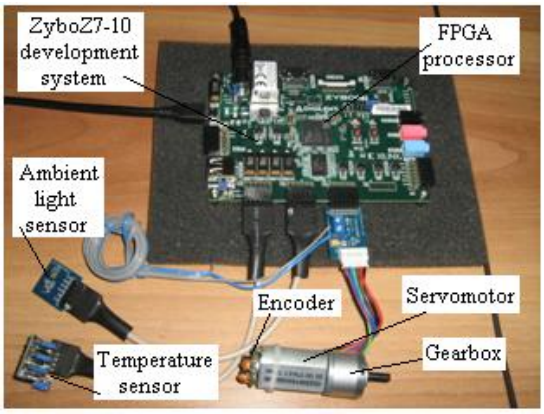

Figure 7 – RHT-based IB control system configuration

Fig. 8 shows the ZyboZ7-10 development system hardware resources allocation in Vivado HLS for this particular application [11]. There may be observed that the connectors JC, JD and JE are configured for interfacing the Pmods of ambient light sensor, temperature sensor and PWM power converter respectively. Additionally, four slide switches and four LEDs are also interconnected to this embedded FPGA-based development system.

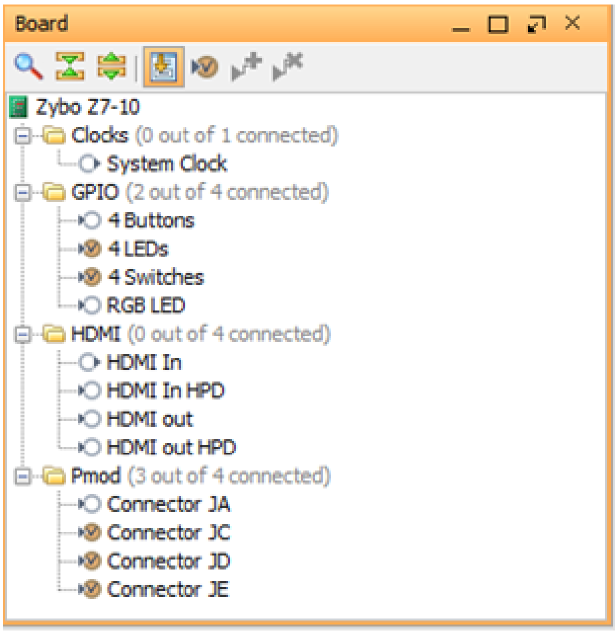

Figure 8 – The ZyboZ7-10 hardware resources allocation for IB control

The full block diagram of the IB control system is presented below in Fig. 9. This hardware architecture is based on several IP-type predefined circuits interconnection on RHT-based framework. Such approach ensures high versatility and flexibility for the entire control system, the topology being full adaptable for the most demanding user needs if required.

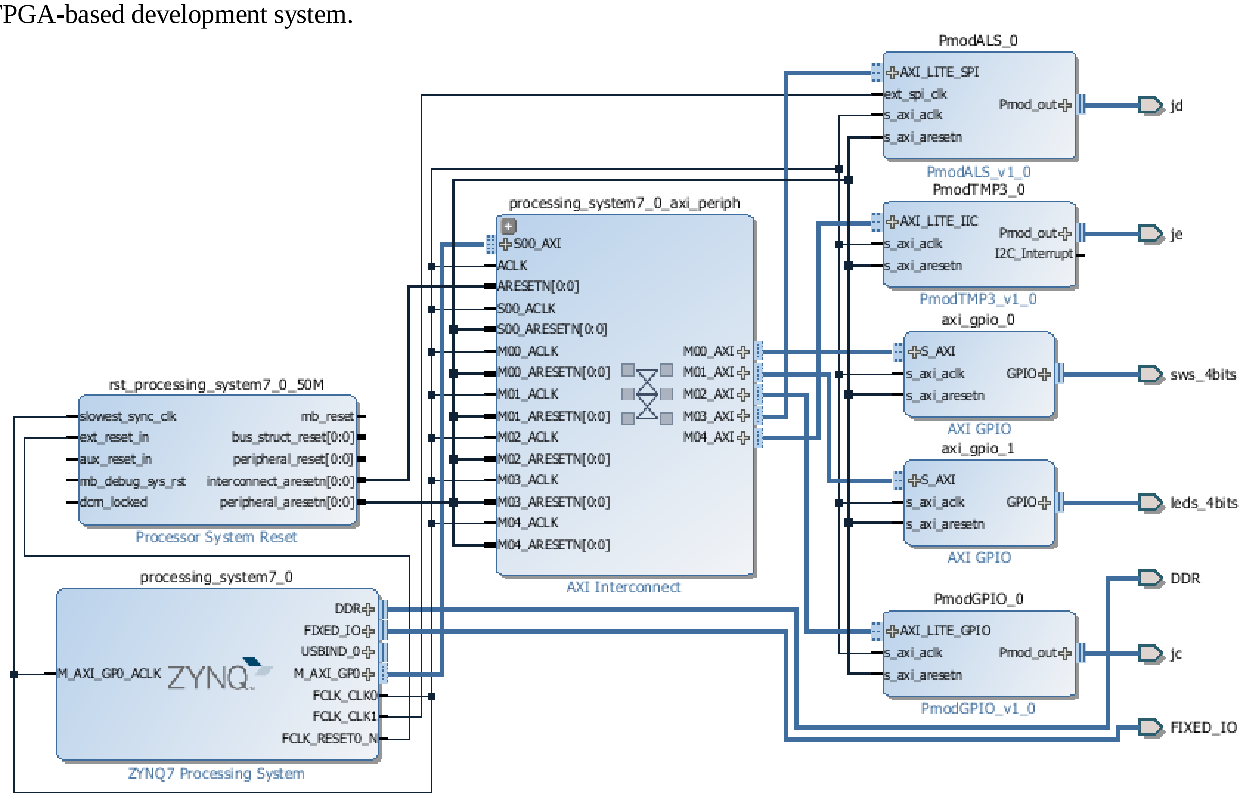

Figure 9 – The block diagram of the IB hardware control system

DOI: 10.17667/riim.2020.1/1.

In this way through relatively simple reprogramming operations a wide range of IB control structures and topologies may be achieved upon the same RHT-based hardware framework. In other words, the number (and type) of interfaced circuits, sensors, buttons, control modules, switches, or other electrical devices can be varied and changed arbitrarily in order to fulfill the most demanding life standard requirements of IB inhabitants. In addition, even under influence of a continuously changing environment the RHT-based IB control system can operate properly because of its high-level versatility and adaptability for a wide range of smart building applications. The *C* code software used for IB control is shown next in Fig. 10. In left side of this picture are plotted the newly generated hardware structures that evidences the full development and implementation steps required in Vivado SDK [12]. Right side is listed a short part of the corresponding driver program for data acquisition and servomotor control.

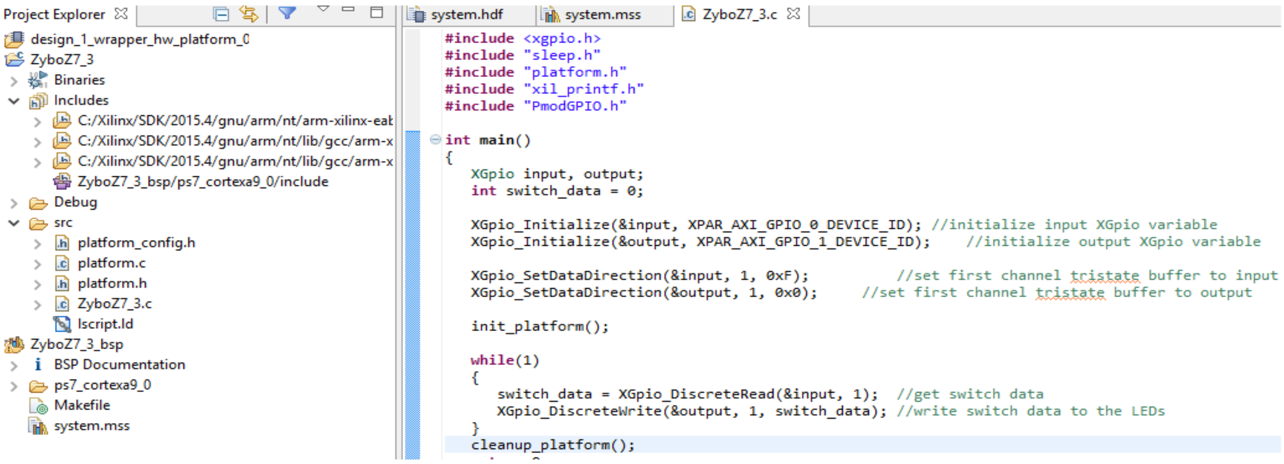

Figure 10 – A piece of the C-source program for the IB control developed under the Vivado SDK toolkit

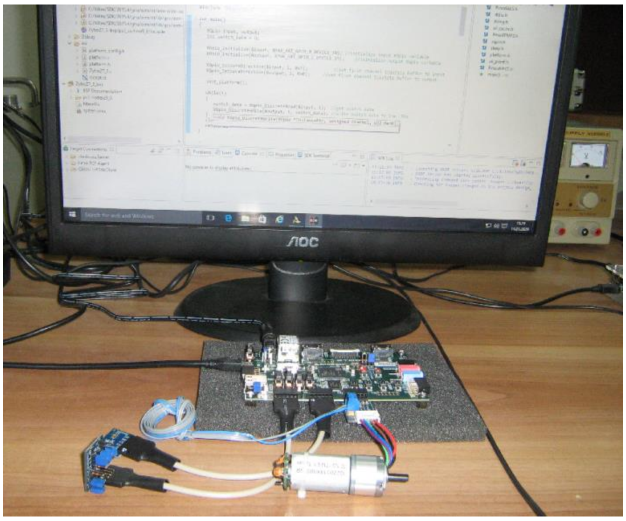

Figure 11 – The laboratory setup that reproduces the IB control system

Finally, in Fig. 11 is presented a picture that imitates on a laboratory scale the IB control system designed upon the RHT-based framework provided by the last generation ZyboZ7-10 development system.

V. Conclusions

The paper approaches the idea to focuses modern IBs development and implementation strategies under constraints of a CPS context. Therefore, it is emphasized the viewpoint to perceive smart buildings design and development as distributed systems or CPSs rather than a set of complex mechatronic systems that operates inside the considered IBs. In this endeavor the RHT-based implementation paradigm can become a useful and welcome support to deal with complexity and heterogeneity of IB control systems. Of course, the presented experimental setup does not cover at all the full complexity and difficulties of such developments but may be considered as an intuitive example of how to approach next generation IBs implementation and development.

References

[1] A.T.P. So, W.L. Chan, “Intelligent Building Systems”, *Kluwer Academic Publishers*, Massachusetts 02061 USA, 1999.

[2] http://web.itu.edu.tr/~onaygil/ebt614e/IB_Definition.pdf

[3] S. Wang, “Intelligent Buildings and Building Automation”, *Spon Press*, New York, USA, ISBN: 0-203-89081-7, 2010.

[4] A.T.P. So, A.C.W. Wong, K-c. Wong, "A new definition of intelligent buildings for Asia", *Facilities*, Vol. 17 Iss: 12/13, ISSN: 0263-2772, pp.485 – 491, 1999.

[5] T.D.J. Clements-Croome. “What do we mean by intelligent buildings?” *Automation in Construction*, vol. 6, pp. 395–399. 1997.

[6] A. Harrison, E. Loe, J. Read, “Intelligent buildings in South East Asia”. *E & FN Spon*, London, 1998.

[7] W.M. Kroner, “An intelligent and responsive architecture”, *Automation in Construction*, vol. 6, pp. 381-393, 1997.

[8] Cs. Szász, G. Husi (2014) – *The Intelligent Building Definition: A Central European Approach*, 2014 IEEE/SCIE International Symposium on System Integration, December 13-15, Tokyo, Japan, ISBN: 978-1-4799-6942-5, DOI: 10.1109/SII.2014.7028040, pp. 216-221.

[9] G. Husi, Cs. Szász, V. H. Hashimoto (2014) – *Application of reconfigurable hardware technology in the development and implementation of building automation systems*, Environmental Engineering and Management Journal, November 2014, Vol. 13, No. 11,

[10] https://www.xilinx.com/products/design-tools/vivado.html

[11] https://www.xilinx.com/products/boards-and-kits/1-pukimv.html

[12] https://www.xilinx.com/support/documentation/sw_manuals/xilinx2015_1/SDK_Doc/index.html