"Gheorghe Asachi" Technical University of Iasi, Romania

APPLICATION OF RECONFIGURABLE HARDWARE TECHNOLOGY IN THE DEVELOPMENT AND IMPLEMENTATION OF BUILDING AUTOMATION SYSTEMS

Géza Husi[1*], Csaba Szász[2], Hideki Hasimoto[3]

[1]*University of Debrecen, Faculty of Engineering, Department of Electrical Engineering and Mechatronics, 2-4 Ótemető Street, Debrecen, Hungary*
[2]*Technical University of Cluj, Faculty of Electrical Engineering, Department of Electrical Machines and Drives, Str. Constantin Daicoviciu nr 15, 400020 Cluj - Napoca, Romania*
[3]*Chuo University, Faculty of Science and Engineering, Department of Electrical, Electronic, and Communication Engineering, 742-1 Higashinakano Hachioji-shi, Tokyo 192-0393 Japan*

Abstract

Due to the continuously increasing trend in the costs of the traditional fossil fuels, the development of residential or commercial buildings with reduced energy needs becomes a significant and more pressing scientific challenge. At the same time, consumers are increasingly demanding more comfortable buildings, where the energy needs are addressed using locally available renewable energy resources. Consumers also require a higher level of security, supervision, and control of the building, depending on the needs of the users. The abovementioned expectations present building automation systems design engineers with a challenging situation, which is difficult to approach using classical methods or strategies. As a result, this paper outlines novel facilities and solutions offered by the current level microelectronics in building mechatronics systems development and implementation. In the first step of this endeavor, the benefits of the reconfigurable technology are highlighted and explained. Next, available hardware resources are presented, especially examining the novel FPGA processors-based architectures suited for building automation applications. The feasibility and versatility of such a reconfigurable hardware configuration and parallel computing digital system were tested in a concrete building supervising and control application. The experimental results met the designers' expectations, indicating that the proposed hardware represents a viable solution for a wide range of high performance building automation systems design and development.

Key words: intelligent building, FPGA processor net zero-energy, parallel computing, reconfigurable technology

Received: February, 2014; Revised final: October, 2014; Accepted: October, 2014

1. Introduction

Rising energy prices have led to interest in building efficiency, and buildings that produce as much energy on-site as they consume are becoming increasingly common. In certain countries, nearly 30 to 40% of the nation's energy is consumed by residential or commercial buildings. Making such buildings more energy-efficient would not only save expenses but also drastically reduce carbon emissions.

The net-zero energy is a general term applied to a building with a net energy consumption of zero over a typical year. In such buildings, the amount of energy provided by on-site renewable energy is equal or even greater than the amount of energy used by the building (typically obtained from traditional fossil fuels). By the purest definition, a net-zero building (NZEB) produces all of the energy required on site using renewable energy sources, and it draws no more power from the grid than it gives back by generating

* Author to whom all correspondence should be addressed: husigeza@eng.unideb.hu

energy from non-polluting locally available resources (Deru and Torcellini, 2004; Torcellini et al., 2006).

Therefore, projects and research efforts that are involved in the development of net-zero energy buildings are highly welcome and reflect a continuously emerging trend of this research area, becoming an important task of the engineering community. Obviously, buildings that use non-polluting sources that generate energy onsite, embedding complex heating, ventilation, and air conditioning (HVAC) systems, supervising and event monitor systems, or other complex automation systems that operate together to achieve the above mentioned net-zero energy goal are termed in international references as "intelligent buildings" (Barley et al., 2005; Deru and Torcellini, 2006).

An intelligent building includes various features, such as climate control, modern lighting technologies, energy supply and its control systems, building security and supervising systems, monitoring system for the doors and windows, the use of renewable energy sources, internal- and external-sensors, data acquisition and data processing systems, computer networks, remote control systems, and digital control systems.

All of the abovementioned complex systems assumes the latest generation of building automation technologies capable of implementing real-time control methods and strategies. This immense challenge pushes building mechatronics development engineers into a difficult situation. On one hand, such engineers are highly interested and focused to determine the most adequate microelectronic technologies suitable for intelligent buildings complex automation systems development and implementation. On the other hand, such digital technology must be integrated into the entire system to support of the entire HVAC, supervising, and events monitoring networks.

Using integrated design and building technologies, designers are able to determine which energy efficiency strategies and what type of renewable on-site generation will contribute to higher energy performance to meet the NZEB requirements of the building considered.

2. Background and infrastructure of the research and development

For the research and development activities described in this paper, the resources at the Building Mechatronics Research Center of the Electrical Engineering and Mechatronics Department at Debrecen University are utilized. The center includes an intelligent building infrastructure, as described in the block diagram of Fig. 1 (Husi et al., 2013). This building embeds building automation and HVAC control systems, climate control and lighting technologies, a building security and supervising system, the energy supply and its control systems, sensor systems, data acquisition and data processing systems, computer networks, and renewable energy sources.

One of the used renewable energy sources is the locally available solar energy captured using flat solar energy collectors and solar tube collectors installed on the building's back terrace and from a swivel-stand photovoltaic array mounted in the garden of the building (http://www.eng.unideb.hu/vmt2/).

In addition, a high capacity heat pump system provides heat energy that is stored in several hot water tanks mounted in the intelligent building's basement. The duct system is mounted in the building's ceiling with the adequate pipes, and the heat pump's condenser, the evaporator, the expansion valve, and the compressor are mounted into a cabinet.
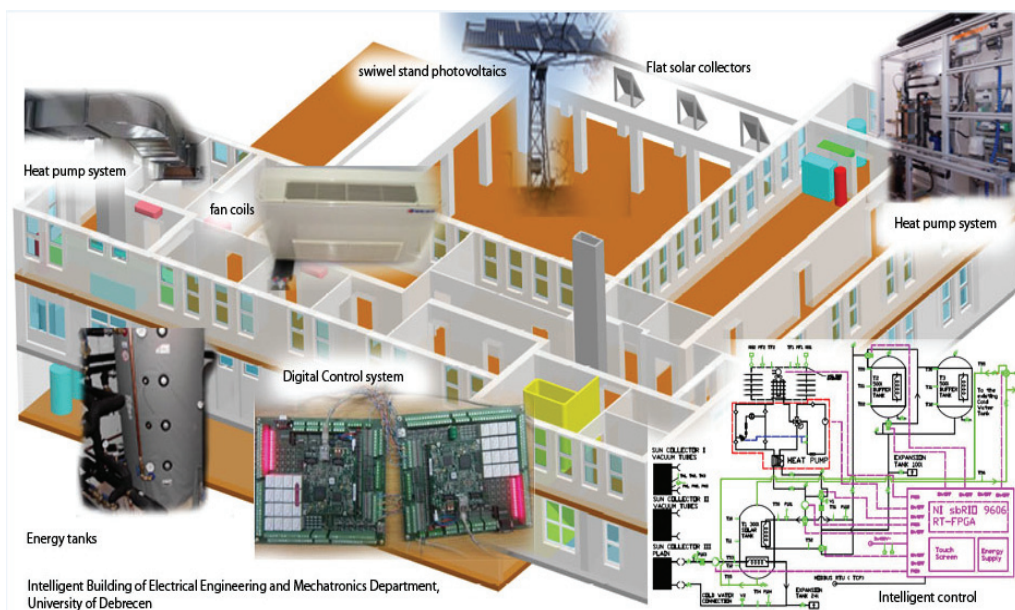

Fig. 1. Intelligent building infrastructure developed at the Building Mechatronics Research Center, Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University

Using net-zero energy strategies, the yearly energy consumption of this building (the Building Mechatronics Research Center) is proposed to be fully covered from the abovementioned locally available renewable non-polluting energy sources. One of the first major obstacles in this endeavor is that it is not evident what type of physical hardware support and microelectronic technology is the most adequate for the complex building automation system implementation.

The real-time control implementation requirement must be balanced with the parallel and distributed execution of a high number of controls, monitoring, supervising, or network communication tasks. Moreover, it is well-known that building's structure, internal functionality, HVAC system type implemented, renewable energy sources used, or desired automation-supervising-monitoring level required, widely differ from each other. Therefore, it would be more efficient and practical (and convenient at the same time) to use a general-purpose hardware system architecture that can adequately implement and execute all the processing requirements described in the previous paragraph under the "intelligent building" concept definition.

In other words, the primary goal of this paper is to propose a general-valid hardware system framework that possess sufficient capability and has the ability to "learn and adapt to" each building's specific mechatronics system structure and building automation level implementation requirements. In other words, the same hardware framework must be able to fulfill a wide range of building automation applications in different types of residential or commercial buildings.

3. Reconfigurable technology, a versatile solution in building automation

Reconfigurable computing is one of the most important and challenging paradigms of current level microelectronics and digital technology. Combining some of the flexibility of software with the high performance of hardware, reconfiguration is characterized by the ability of hardware architectures to rapidly change the functionality of their internal structure and the wiring configuration between its modules after customer needs.

Reconfigurable computing offers huge advantages, such as speed, flexibility, low-power consumption, ease of scale, and adaptability, and represents the modern solution to many computationally intensive tasks in automation and mechatronics systems development. High-performance reconfigurable systems also have the potential to exploit coarse-grained functional parallelism as well as fine-grained instruction level parallelism, using custom computing technologies.

As it is well-known, FPGA (Field Programmable Gate Arrays) circuits are the most general purpose reconfigurable processors and play a leading role in reconfigurable computing strategies implementation. FPGAs are ideally suited for the network computing and distributed tasks solving that is highly required in complex automation systems development and implementation.

The above-mentioned theoretical remarks outline parallelization and parallel computing as one other special attributes of today's microelectronic technology, which are well-suited for a large amount of complex real-time and multitasking processing applications. Such reconfigurable hardware architectures provide a cost-effective solution for computationally intensive applications. Moreover, FPGAs are well placed to be at the heart of high performance parallel computing and packet processing because of their immense computational efficiency matched by rich on-chip interconnectivity, high bandwidth concurrent memory access and complete programmability technologies.

All of these features are achieved by seamless and efficient mapping of system functions and huge re-routing abilities supported by a programming flow that abstracts the hardware implementation details. Due to its massive potential parallelism, FPGAs also allow multi-grid computation, providing a flexible platform for fine-grained parallel computing; in addition, FPGAs allow hardware level wiring of decision logic, and it excels in integer arithmetic computing. Therefore, its hardware configuration is exemplary for logic intensive tasks that do not require floating point calculations.

Summarizing the above expressed theoretical remarks, reconfigurable computing combined with parallelization will undoubtedly play a determinant role in the high performance and processing intensive real-time control applications implementation in mechatronics. From this point of view, at the current level digital electronics technologies, FPGA chips represent the perfect solution with which to implement highly concurrent control, communication, monitoring, and supervising task required in intelligent buildings automation systems because they are VLSIs built inherently with massively parallel structures with a powerful hierarchy of customer reconfigurable interconnection networks.

Therefore, a feasible approach is to use FPGA-based hardware architectures for building automation systems development and implementation, where flexibility and hardware reconfiguration are highly important issues. Hence, this paper proposes to use the ability of hardware architectures to rapidly change the functionality of their internal structure and the wiring configuration between its modules after customer needs, i.e., instead of implementing various hardware architectures for different residential or commercial building configurations and with different level of automation, only a basic configuration digital system will be used for a large scale of building automation development. In other words, the key concept is that

by using reconfigurable technology, the physical hardware support should be able to "learn and adapt to" each buildings specific mechatronics system structure and building automation application.

4. Reconfigurable technology hardware system development for implementation of building automation

Fortunately, current level microelectronic technologies enable designer engineers involved in building automation systems to avoid complex hardware design efforts. There are a large set of commercially available FPGA-based development boards possessing a large amount of powerful hardware resources suitable to fulfill, in detail, a wide range of expectations. Therefore, it appears to be appropriate to use a versatile FPGA-based development board already possessing a great amount of integrated hardware resources and well-suited to fulfill a wide range of customer needs.

Such a solution contains, from the starting point, several important advantages: powerful hardware resources with immense interconnection flexibility, high reliability in expert quality, low-cost implementation, low-power consumption, full compatibility with the latest generation programming technologies, powerful display and communication capabilities, and not least of all, user-friendly development behaviors. In addition, the latest generation FPGA platforms have capabilities that offer tight integration of the processor chip, the programmable logic, and the memory. All the above are also confirmed by the generally accepted theoretical remarks that underline FPGA board roles as ideal candidates for reconfigurable platforms implementation with large distributed and parallel processing capabilities.

5. Experimentation of a building supervising system by using reconfigurable technology and a LabVIEW software-based model

National Instruments' software and hardware are well suited to initiate the high level and technically sustainable development and infrastructure described in this paper. Our Department and the Faculty of Engineering rely on the technologies provided by National Instruments. The Faculty provides LabVIEW tuition to each student for at least a semester.

The units driven by renewable energy are controlled by an NI compact controller. For this project, we chose the NI sbRio technology, which is an FPGA-based technology, which are reconfigurable, parallel working real-time embedded controllers.

NI sbRio 9606 Card (Fig. 2) integrated into heat pump system includes:
- 400 MHz processor, 512 MB non-volatile storage;
- 256 MB DRAM for deterministic control and analysis;

- Reconfigurable Xilinx Spartan-6 LX45 FPGA for custom timing, inline processing, and control;
- 96 3.3 V DIO lines;
- Integrated 10/100BASE-T Ethernet, RS232 serial;
- CAN, and USB ports; 9 to 30 VDC supply input;
- from -40 to 85 °C local ambient operating temperature range.

Fig. 2. NI sbRio 9606 Card

The NI sbRIO-9606 embedded control and acquisition device integrates a real-time processor, a user-reconfigurable FPGA, and I/O on a single printed circuit board (PCB) (Fig. 3). It features a 400 MHz industrial processor, a Xilinx Spartan-6 LX45 FPGA, and a RIO Mezzanine Card connector, which is a high-speed, high-bandwidth connector providing direct access to the processor and 96 3.3 V digital I/O FPGA lines.
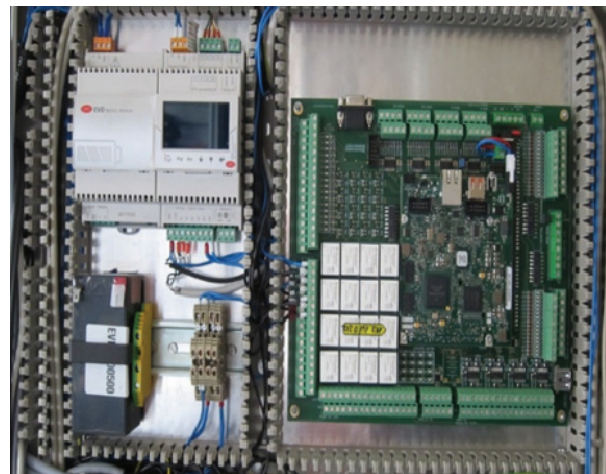

Fig. 3. NI sbRio 9606 Card on the carrier panel

This device features a built-in 10/100 Mbit/s Ethernet port that can be used to conduct programmatic communication over the network and host built-in web (HTTP) and file (FTP) servers. The sbRIO-9606 also features integrated CAN, RS232 serial, and USB ports for controlling peripheral devices (National Instruments, 2013).

The professionals of Energotest built a carrier for the "mother card":
- 32 digital inputs;
- 16 Push-pull outputs, 16 relay outputs;
- 16 PWM (analog) outputs;
- 32 (16 differential) analog inputs.

The system is realized on printed circuits. The system also has a standby battery. Regarding performance, the system is similar to the sbRio 964x. The overall amount of the execution: 40 hours + 25 technician hours. Because of the drastic decrease of the information technology solutions and the increase of individual solutions, the FPGA provides a flexible and reconfigurable system, which can extend the life of the electronic devices used.

The NI LabVIEW platform provides the option to create real time simulation systems in parallel processing. With the appropriate extensions, the LabVIEW (short for Laboratory Virtual Instrumentation Engineering Workbench) is a system design platform and development environment for a graphical programming language from National Instruments.

The programming language used in LabVIEW, also referred to as G, is a dataflow programming language. Execution is determined by the structure of a graphical block diagram (the LV-source code) on which the programmer connects different function-nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available. Because this might be the case for multiple nodes simultaneously, G is inherently capable of parallel execution. Multi-processing and multi-threading hardware is automatically exploited by the built-in scheduler, which multiplexes multiple OS threads over the nodes that are ready for execution.

The graphical programming user interface and philosophy provides further didactic opportunities. LabVIEW has plenty of implementations in industry, as it can be used to test many important aspects of mechanical signals and systems, e.g., stress, strain, heat dissipation, moments and fluid dynamics. Information can be logged and rigorous automated DAQ (Data acquisition) schemes can be implemented entirely from within the LabVIEW environment.

Our department colleagues also develop Object oriented programs (Building-Mechatronic) in LabVIEW environment. The fully modular character of the LabVIEW code allows reusing code without modifications: as long as the data types of input and output are consistent, two sub VIs are interchangeable and it can increase the productivity. Building Mechatronics simulation system has two sbRio FPGA card controllers: Master and Slave. The Master is for measurement control and makes building engineering simulation. The Slave is responsible for the regulation, the broadband communication and the treatment failure. In this manner, a wide-range Building Mechatronic simulation is created (Fig. 4).

The Master sbRio (Test controller) is the communication master, which produces building simulation by sensors, actuators, building engineer modeling and uploads the test exercise to the data base. The Slave sbRio (DUT: Device Under Test) provides the communication tests, the test of the

regulation functions and exercises as well as the test of the maintenance and alarm functions (Husi and Szász 2013).
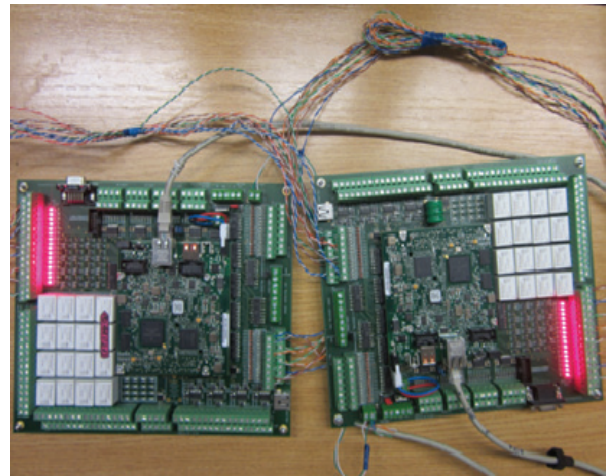

Fig. 4. The Master and Slave sbRio cards

The advantages of choosing NI FPGA based technology are as follows: sbRio is a real-time, parallel processing embedded device. The LabVIEW software provides the development of the programs on PC with TCP/IP. The Slave sbRio software is embedded into building engineering/ building management system without modification. The LabVIEW software can communicate directly with SQL-compatible data base. In other words, NI FPGA based technology can realize direct data collecting and analysis.

We have chosen NI LabVIEW and sbRIO because of their reliability and ease of implementation (Fig. 5). Furthermore, the software development is not difficult, and the price/performance ratio is high. Another reason for this choice was to find easily implemented devices that have low software complexity, which enables our students to learn quickly.

The Mechatronics Department uses the National Instruments devices in various fields in education, e.g., the ELVIS technology is used in the education of digital circuits or for measurement and data collection for mechatronic projects.

6. Building mechatronics simulation system

In accordance with the adopted development strategy, the first layer implementation requires the input information regarding the architectural features and specifics of the building considered for the experiment. For this reason, a LabVIEW software-based supervising and event monitor system was designed, the input information of which is considered the building's cadastral plan in a .jpeg or .bmp file format. This plan indicates all the building rooms, the sizes of the rooms, annex buildings, and existing basements, the number of doors and windows, or other important particularities.

The program fixes this file on the design desktop of the LabVIEW toolkit and places it as a background element. At the same time, it is also necessary to indicate the placement of the lighting elements, the fan coils, or other heating elements arrangement in the building. If this information is available, the designer marks all of them on the desktop, as shown in figure 6. In this study, an arbitrary chosen building plan is indicated, freely downloaded from the www.schwabinvest.hu internet page. The graphical elements placed on the desktop surface are arranged according to the following rules:

- the doors are marked with green squares;
- the windows are marked with blue squares;
- the lighting elements are marked with yellow circles;
- the motion sensors are marked with gray oval circles;

- the fan coils and heating elements are marked with red squares.

In the considered building are also placed motion detection sensors; if there are no persons in the building (or at nighttime) the entrance door and all the lighting elements switches off. The sensors can be programmed for arbitrary timing intervals, and the garage doors closes automatically as well.

The program supervises the statuses of all the doors and windows (open or closed), the lighting system of the building, and the state of the heating elements (turn off/turn on). This monitoring system can be arbitrary linked with the alarm system of the building. In the given example, the alarm system operates only if all of the windows of the building are closed; otherwise, it turns off and indicates this state. Of course, according to the customer needs, the building alarm system could be operated after any other programmed logic required.
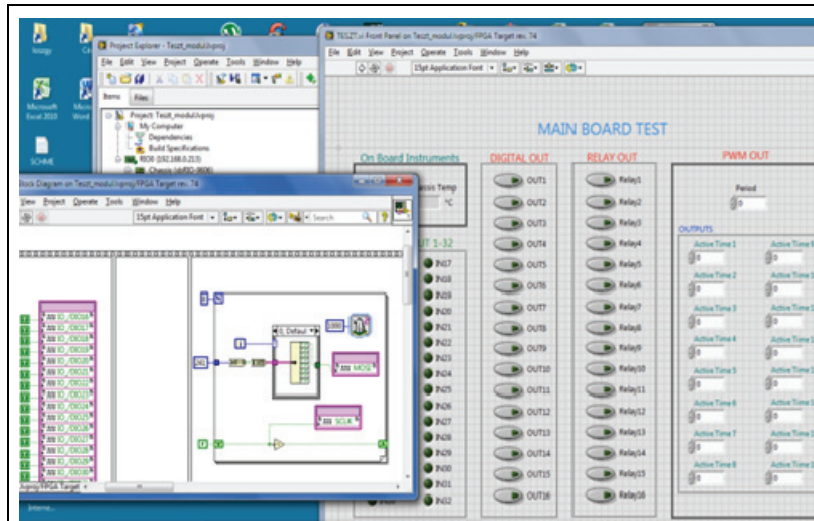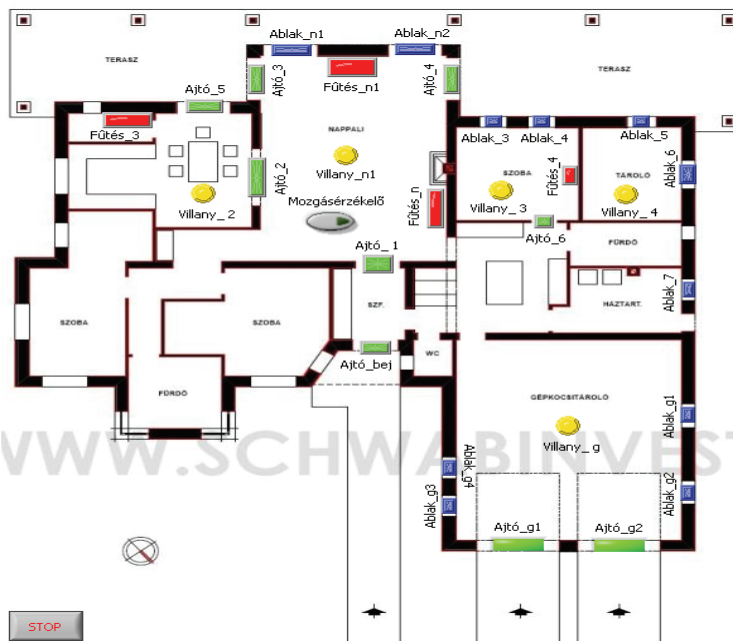

Fig. 5. LabVIEW graphical environment

Fig. 6. The arrangement of the LabVIEW graphical elements on the design surface

7. Conclusions

This paper outlined the benefits of the reconfigurable hardware technology application in building automation systems development and implementation. The discussion outlined the notable possibilities offered by the microelectronics of the latest generation of reconfigurable technologies. A special hardware system based on the architecture of FPGA processors-based NI SbRIO master-slave cards was tested.

The feasibility and versatility of such a reconfigurable hardware configuration and parallel computing digital system were tested in a concrete building supervising and control application. The experiments met the designers' expectations, thus demonstrating that the proposed system offers a viable solution for a wide range of high performance building automation systems design and development.

Acknowledgments

References

Barley C., Deru M., Pless S., Torcellini P., (2005), *Procedure for Measuring and Reporting Commercial Building Energy Performance*. Technical Report NREL/TP-550-38601, Golden CO: National Renewable Energy Lab. On line at: www.nrel.gov/docs/fy06osti/38601.pdf

Deru M., Torcellini P., (2004), *Improving Sustainability of Buildings through a Performance-based Design Approach*, Preprint NREL Report No CP-550-36276, World Renewable Energy Congress VIII, Denver, CO, On line at: http://www.nrel.gov/docs/fy04osti/36276.pdf.

Deru M., Torcellini P., (2006), *Improving Sustainability of Buildings through a Performance-based Design Approach*. Technical Report NREL/TP-550-38617, Golden CO: National Renewable Energy Lab. On line at: www.nrel.gov/docs/fy04osti/38617.pdf

Husi G., Szász Cs., (2013), *Building Automation Technology in Electrical Engineering and Mechatronics Department in Debrecen*, Ulusal Makína Teorisi Sempozyumu, 12-13 Eylül, Erzurum, 671-674.

Husi G., Szemes P.T., Tóth N., Dudás É., (2013), *Establishment of New Research Infrastructure at Department of Electrical Engineering and Mechatronics, Faculty of Engineering, University of Debrecen,* Proce. of the Annual Session of Scientific Papers, Volume XII (XXII) "IMT Oradea" Felix SPA, Oradea, Romania.

National Instruments, (2013), Technical Reports: The official site of NI SbRIO-9606, On line at: http://sine.ni.com/nips/cds/view/p/lang/hu/nid/210003

Torcellini P., Pless S., Deru M., Crawley D., (2006), *Zero Energy Buildings: A Critical look at the Definition*. ACEEE Summer Study, Pacific Grove, California, NREL/CP-550-39833, Online at: http://www.nrel.gov/docs/fy06osti/39833.pdf.