Habilitation Thesis

Low Power Electrical Drives Digital Control Systems Development and Implementation

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CONTENTS

THESIS SUMMARY

The habilitation thesis presents the scientific activity and research results obtained since the defense of the Ph.D. thesis in April 1999 to 2014, when the habilitation was printed. It is a short overview of the scientific contributions and achievements during this period, outlining the most significant activities and research efforts performed over the last fifteen years in the Electrical Engineering Faculty, from Technical University of Cluj.

In the first paragraph of the thesis the habilitation request motivation is shortly unfolded. The paragraph presents the professional experience gained during over these years, covering important theoretical knowledge and experimental skills in the mentioned scientific domain. A high number of publications including papers at international conferences, books, a patent, ISI quoted papers or research grants confirms the quality of the research and scientific activity being undertaken. The habilitation request is also motivated by the important research experience gained in international universities as invited researcher.

The second paragraph offers a brief presentation of the research areas chosen and competences gained. These research areas and competences are in Electrical Engineering, focusing mainly on the scientific domain of the Electrical Drives Digital Control Systems development and implementation. This is a multi-disciplinary research field where important theoretical and experimental competences have been gained in topics such as: pulse width modulated converters design and implementation for low-power electric motors, servomotor-based electrical drive systems development and implementation, microprocessor architectures-based digital control systems design and implementation (Intel processors, microcontrollers, FPGA processors, PLCs, etc.), fault-tolerant low-power electrical drives experimentation, or building mechatronics and automation systems implementation.

The third paragraph is dedicated to areas of competence complementary to electrical engineering. It is mentions the important theoretical and experimental knowledge gained in this period in the area of biologically-inspired digital control systems development and implementation (embedding high performance real-time parallel and distributed computing hardware architectures) for fault-tolerant electrical derives experimentation. Additionally it is outlined the experience in digital control systems programming (LabView graphical software toolkit, assembly language, VHDL, PLC ladder-logic, micropascal, etc.).

The memoir of the technical-scientific activity and research results is presented in the fourth paragraph of the thesis. It highlights the area of electrical drives digital control systems development and implementation, with a special attention on servomotors-based systems modeling, simulation, and experimentation. A high number of scientific works are dedicated to dynamic performances evaluation of servomotors-based electrical drive systems, respectively to the modeling and simulation of these systems. Modern control strategies implementation is also widely analyzed and experimented. Among these outstands the vector control strategy, the H_2 robust control strategy implementation for servo drive systems, the sliding-mode robust control or fuzzy control strategies for electrical drive systems, respectively variable structure controllers implementation for closed-loop servomotor-based systems, which are presented and explained in detail in several papers. Important research efforts have been dedicated to the low-power current-source PWM inverter design methodology and experimentation for two-phase bipolar stepping motors widely used in servo drive automation systems. The research was targeted on detailed electronic circuits presentation, simulation results, respectively laboratory measurements of a versatile power electronic module specially conceived for stepping and d.c. motors closed-loop drive. Furthermore, during the postdoctoral research stage a special attention was focused on the linear synchronous motors power converters design, development and implementation. There have been studied special type linear synchronous motors with application in health service tray systems, specially designed and experimented for elderly persons. At the same time, digital control systems development and implementation plays a main role in the scientific and research activities of the above mentioned period. Among the designed and experimented control architectures are mentioned the hardware-in-the-loop configurations built up upon microcontroller-based configurations, implementing real-time PID control strategy, or fractional control algorithms prototyping. Programmable logic controllers-based architectures also are widely used systems in modern industrial control applications. An example of such a development system is described in the thesis. Another important research topic refers to the fault-tolerant electrical drive systems development and implementation. There the main efforts are focused on fault-tolerant power converters and fault-tolerant digital control systems design and experimentation. The basic idea of this topic is to imitate biological organism's self-healing and fault-tolerance behaviors and to implement it in digital silicon structures in order to achieve high reliability control architectures. The research efforts presented in this paragraph have also been financially supported by projects won by the author in national grants competition. Last but not least, the human-computer interaction technologies implementation in electrical drive systems is an important research task of the mentioned period. There multimodal communication abilities (such as voice recognition and image processing) have been implemented in a specially developed mobile robot. This research proves that if the robot is endowed with multimodal communication abilities it becomes suitable to exhibit more intelligence and additional cooperativeness in its behavior.

Paragraph five indicates the main directions for career development which require the habilitation. There it is mentioned that in the future career development will be followed the same area of the Electrical Drives Digital Control Systems development and implementation in Electrical Engineering. This scientific domain includes main topics such as PWM smart converters design and implementation for low-power electric motors, servomotor-based electrical drive systems development and experimentation, microprocessor architectures-based digital control systems design and implementation. At the same time it is expected that in the future career development higher attention and research efforts will be focused on the fault-tolerant electrical drive systems design and experimentation. This line of research also considers the fault-tolerant low-power electrical drives experimentation and bio-inspired digital control systems development and implementation for critical electrical drive applications.

REZUMATUL TEZEI

Teza de abilitare prezintă activitatea ştiinţifică şi de cercetare desfăşurată după susţinerea tezei de doctorat în aprilie 1999 şi până în prezent în anul 2014. Este o succintă trecere în revistă a contribuţiilor ştiinţifice şi a rezultatelor obţinute în cercetare pe o perioadă de aproximativ 15 ani la Facultatea de Inginerie Electrică din cadrul Universităţii Tehnice din Cluj.

În primul paragraf al tezei este descris pe scurt motivarea cererii de abilitare în Inginerie Electrică. Aici este menţionat experienţa profesională acumulată în perioada anterior amintită, cu cunoştinţe teoretice şi aptitudini experimentale importante în domeniul ştiinţific în care se desfăşoară activitatea. Această experienţă este susţinută printr-un număr mare de publicaţii la conferinţe internaţionale, cărţi de specialitate, brevet de invenţie, lucrări ştiinţifice în reviste cotate ISI, sau granturi de cercetare în care sa lucrat. Cererea de abilitare este motivată şi de experienţa internaţională importantă în universităţi din străinătate ca şi cercetător invitat.

Al doilea paragraf cuprinde o scurtă prezentare ale domeniilor de cercetare şi a competenţelor acumulate în aceste domenii. Aceste domenii de cercetare sunt în Inginerie Electrică, focalizat în special spre dezvoltarea şi implementarea Sistemelor de Reglare Digitale ale Acţionărilor Electrice. Aceasta este un domeniu de cercetare multidisciplinar unde s-au acumulat cunoştinţe teoretice şi abilităţi de experimentale importante în tematici ca: proiectarea şi experimentarea invertoarelor cu modulaţie în durată a impulsurilor pentru motoare electrice de putere mică, dezvoltarea şi implementarea acţionărilor electrice bazate pe servomotoare, proiectarea şi implementarea sistemelor de control digital bazate pe arhitecturi te tip microprocesor (procesoare Intel, microcontrolere, procesoare FPGA, automate PLC, etc.), experimentarea acţionărilor electrice tolerante la defecte, sau implementarea sistemelor automate pentru mecatronica clădirilor.

Paragraful al treilea este dedicat domeniilor de competenţă complementare ingineriei electrice. Aici este menţionat experienţa teoretică şi experimentală acumulată în această perioadă în domeniul dezvoltării şi implementării sistemelor digitale de inspiraţie biologică (având înglobate arhitecturi hardware pentru procesare paralelă şi distribuită în timp real de mare performanţă) pentru experimentarea acţionărilor electrice tolerante la defecte. Adiţional este remarcat experienţa în programarea sistemelor digitale de comandă (mediul grafic LabView, limbajul de asamblare, VHDL, diagrama de scară PLC, micropascal, etc.).

Memoriul tehnic al activităţii de cercetare este prezentat în paragraful patru. Este evidenţiat domeniul dezvoltării şi implementării sistemelor de reglare digitale ale acţionărilor electrice, cu accent deosebit spre modelarea simularea şi experimentarea sistemelor bazate pe servomotoare. Un număr mare de lucrări ştiinţifice sunt dedicate evaluării performanţelor dinamice ale acţionărilor electrice bazate pe servomotoare, respectiv pe modelarea şi simularea acestor sisteme. Strategiile moderne reglare sunt de asemenea pe larg analizate şi experimentate. Printre acestea se remarcă strategia comenzii vectoriale, reglarea robustă H_2 pentru servomotoare, implementarea regulatoarelor cu alunecare şi de tip fuzzy în acţionări electrice, respectiv implementarea regulatoarelor cu structură variabilă, care sunt prezentate în mai multe lucrări ştiinţifice. Eforturi de cercetare semnificative au fost dedicate pentru proiectarea şi experimentarea invertoarelor PWM sursă de curent pentru motoarele electrice de mică putere utilizate în servosisteme de acţionare. Aici sunt prezentate circuite electronice detaliate, rezultate de simulare numerică, respectiv măsurători de laborator a unor module electronice de putere special concepute pentru alimentarea servomotoarelor de curent continuu şi pas cu pas. În stadiul de cercetare postdoctoral o atenţie deosebită a fost acordată proiectări şi implementării convertoarelor de putere pentru motoarelor sincrone lineare. Aici s-au studiat motoare lineare speciale aplicate în domeniul medical, proiectate pentru persoane în vârstă sau cu dezabilități. De asemenea, dezvoltarea şi implementarea sistemelor de reglare digitală a ocupat un loc central în activitățile de cercetare desfăşurate în ultimii aproximativ 15 ani. Printre arhitecturile hardware proiectate şi experimentate se menționează structurile de tip ”hardware-in-the-loop” construite pe structuri digitale de tip microcontroler, implementând strategii de reglare PID în timp real, sau experimentarea regulatoarelor fracționare. Sistemele de comandă şi reglare digitale bazate pe controlerele logice programabile PLC sunt foarte mult folosite aplicațiile de automatizare moderne. Un exemplu de proiectare a unui asemenea sistem este descris în teza de abilitare. O altă temă de cercetare importantă se referă la dezvoltarea şi implementarea sistemelor de acționare electrică tolerante la defecte. Aici eforturile de cercetare s-au concentrat spre proiectarea şi experimentarea convertoarelor electrice şi a sistemelor digitale tolerante la defecte. Ideea de bază a acestei teme este de a imita abilitățile de auto-vindecare şi de supraviețuire ale organismelor biologice din natură şi de a implementa aceste proprietăți în structuri digitale, obținând astfel sisteme de reglare de înaltă fiabilitate. Eforturile de cercetare prezentate în acest paragraf au fost sprijinite financiar şi prin două proiecte de cercetare câştigate prin competiție națională. Nu în ultimul rând, implementarea tehnologiilor de comunicare om-computer în acționări electrice a constituit o temă importantă a activităților de cercetare don perioada descrisă. Aici s-au implementat abilități de comunicare multimodală (recunoaşterea vocii şi a procesării imaginii) pe un robot mobil. Cercetarea a demonstrat că robotul înzestrat cu abilități de comunicare multimodală manifestă mai multă inteligență şi cooperare cu mediul înconjurător.

Paragraful cinci indică pe scurt direcțiile principale de dezvoltare a carierei viitoare care necesită abilitarea. Aici este menționat că în cariera viitoare se va urmării aceeaşi direcție a dezvoltării şi implementării sistemelor de reglare digitale ale acționărilor electrice, în domeniul Ingineriei Electrice. Acest domeniu ştiințific include subdomenii ca: proiectarea şi implementarea convertoarelor PWM inteligente pentru motoare electrice de mică putere, dezvoltarea şi experimentarea sistemelor de acționare electrică bazate pe servomotoare, dezvoltarea şi implementarea sistemelor de reglare digitale bazate pe arhitecturi de tip microprocesor. De asemenea, se preconizează că în cariera viitoare o atenție mai sporită se va acorda dezvoltări şi implementări sistemelor de acționare electrică tolerante la defecte. Aici sunt considerate experimentarea acționările electrice tolerante la defecte de putere mică, respectiv dezvoltarea şi implementarea sistemelor digitale de inspirație biologică pentru acționări electrice critice.

Conf. dr. ing. Szász Csaba

I. HABILITATION REQUEST MOTIVATION

This habilitation thesis is a summary of the research performed over a period of fifteen years, covering the time interval since the defense of the Ph.D. thesis in April 1999 to 2014, when the habilitation was printed. The thesis presents the context of this work, summaries the contributions and achievements and provides a short insight into this research effort.

The research and professional activity performed during the above mentioned period has been conducted upon the background of the Applied Informatics specialization gained during the Ph.D. studies at the Technical University of Cluj, Faculty of Electrical Engineering. The main research interest was focused on the area of the digital control systems development for low-power electrical drive systems, with the basic goal of designing and implementing servomotor-based digital control architectures. Such a research task involves a highly multidisciplinary point of view, including and covering accurate knowledge from scientific areas such as microelectronics and digital systems, electrical drives, electrical machines, systems theory, electronics, or programming and software implementation technologies. However, the main issue is how to find the most adequate digital control architecture for a given low-power electrical drive application, considering both expenses and reliability criteria. Such a quite not easy objective is not only limited to choose the most adequate digital control unit for an application, but also involves the difficult problems of the real-time processing, various hardware architectures interfacing, sensors system interconnection, signal processing and data acquisition, microprogramming, real-time control algorithms development, or high-level software technologies implementation. Therefore, from the designer point of view it supposes a wide range of abilities and skills from several important scientific areas strongly linked with each other not only on the theoretical conception stage but at the implementation and experimentation phases as well.

The first stage of the research and professional achievements discussed has been developed immediately after the defending of the Ph.D. thesis, during the period 2000.10.01-2002.04.01. in the framework of a postdoctoral study at the Tokyo University of Technologies (TUAT), Graduate School of Bio-applications and Systems Engineering, Tokyo, Japan. As a winner of a Monbusho Fellowship, I worked as invited researcher at the Environmental and Symbiotic Production Systems Department, TUAT, lead by Prof. dr. eng. Yoshio Kano. There the main research topic was in the area of the Linear Drives Digital Control Systems development and implementation.

After returning to the Electrical Drives and Robots Department of the Electrical Engineering Faculty, Technical University of Cluj in 2002, the research and professional activity has been developed in the Digital Control Systems Laboratory of the same department and institute. This is a new laboratory from the department's infrastructure, which I have built up with the major purpose to explore the specific topic of the novel digital system structures and programmable hardware architectures development, research, and experimentation for complex electrical drive systems implementation and control. A wide range of programmable digital control systems design and development activities has been unfolded, as part of several national and international research projects and grants. Additionally teaching and didactical activities have also been developed for BSc and master degree students of the Electrical Engineering Faculty. Some basic aspects of these research and experimental activities will be briefly presented and discussed in the followings, without the claim of exhausting all the issues.

Considering the above expressed remarks, the habilitation request is motivated by the professional experience gained during a fifteen years research and teaching activity in the area of Electrical Engineering, after defending the Ph.D. thesis in 1999. This experience covers important theoretical knowledge and experimental skills in the mentioned scientific domain, with significant research results both at national and international level. The research results have been published in 101 publications, including 10 books in the topic of digital control systems, electrical drives control systems, or digital electronics; 1 national patent in the field of stepping motor drive converters; 4 ISI papers in high ranked international journals; 19 publications in international or national journals; and 67 conference papers, 21 from these being indexed in international databases (ISI Thomson, IEEE Xplore, etc.). These results are also supported by 11 national and international projects, 8 national and 3 founded by EU. In two of these projects I acted in the capacity as project manager – winner of national grants competition.

Considering the above ranked results and publications, all the minimal criteria imposed to obtain the habilitation are meet, and even exceeding more than two times the minimal criteria for a professor position and habilitation.

The habilitation request is also motivated by the important research experience gained in international universities as invited researcher. Among these outstands the postdoctoral study during the period 2000.10.01-2002.04.01 at the Tokyo University of Technologies, Graduate School of Bio-applications and Systems Engineering, Tokyo, Japan, and the several teaching and research stages from 2008 at Debrecen University in Hungary, as invited lecturer and researcher. In the TUAT the main research topic was linked with the linear motors digital control systems development and implementation. In the Debrecen University, Technical Faculty, Department of Electrical Engineering and Mechatronics studies and research in intelligent building mechatronic systems development and implementation, respectively in human-robot multimodal communication was developed.

An important argument for habilitation is the research and teaching experience gained during the development of the novel Digital Control Systems Laboratory at the Electrical Machines and Drives Department, Faculty of Electrical Engineering, Technical University of Cluj. This new laboratory in the department's infrastructure is specially conceived for low-power electrical drives digital control systems development and implementation. The research infrastructure embeds last generation digital control systems based on Field Programmable Gate Array (FPGA) processors, Programmable Logic Controllers (PLC's), microcontrollers or Intel microprocessors. These systems are used for servomotor control systems implementation of fault tolerant electrical drives development. Additionally, in this laboratory a special attention is focused on the biologically-inspired digital systems development and experimentation for critical electrical drives applications. There has been designed and implemented a specially conceived artificial organism based on a FPGA processors network, which is unique in its architecture at national level. This bio-inspired platform (embryonic system) with a multi-cellular structure reproduces basic properties of biological organisms, such as cell division, cell differentiation, self-healing or fault-tolerance.

In the last fifteen years the main research topics has been developed in the areas of the servomotor-based electrical drive systems implementation, PWM converters design and implementation for low-power motors, microprocessor architectures-based digital control systems design and implementation, fault-tolerant electrical drives experimentation, biologically-inspired digital systems design and development, building mechatronics and automation systems implementation, digital systems programming (LabView, assembly, VHDL, ladder-logic, micropascal, etc.). Considering the important theoretical knowledge and experimental skills gained in the above mentioned areas, the habilitation request is also motivated by these research and development efforts.

II. RESEARCH AREAS AND COMPETENCES

The research areas and competences are in Electrical Engineering, focused mainly in the scientific domain of the Electrical Drives Digital Control Systems development and implementation. This is a multi-disciplinary research field where important theoretical and experimental competences have been gained in the following topics:

- Pulse width modulated (PWM) converters design and implementation for low-power electric motors;
- Servomotor-based electrical drive systems development and implementation;
- Electrical drives direct digital control systems design and implementation (Intel processors, microcontrollers, FPGA processors, PLCs, etc.);
- Fault-tolerant low-power electrical drives design and experimentation;
- Fault-tolerant electrical drives development and implementation – a biologically-inspired approach (embedding high performance real-time parallel and distributed computing hardware architectures);
- Electrical drives digital control systems programming (LabView, assembly language, VHDL, PLC ladder-logic, micropascal, etc.);
- Building mechatronics and automation systems implementation.

A short overview about the above ranked research areas and competences will be presented in the followings.

2.1. PULSE WIDTH MODULATED CONVERTERS DESIGN AND IMPLEMENTATION FOR LOW-POWER ELECTRIC MOTORS

As it is well known, modern electrical drive systems embeds power electronic converters operating in pulse width modulation (PWM) switching mode. Such power converters can be a wide range of rectifiers, inverters, cycloconverters, etc. In this case the development and implementation of special-type inverters for low-power electric motors will be presented. According to a general rule definition the inverters are power electronic converters which transform the direct current energy into alternative current energy. Their input circuit is in direct current and the output in alternative current, mostly operating in PWM principle. The PWM inverters are divided into synchronous and asynchronous types. The synchronous inverters are controlled by synchronous PWM pulses and can be open-loop and closed-loop circuits. The asynchronous inverters operate with asynchronous switching pulses and they have a current-source character (in the output circuit it is reproduced the imposed reference waveforms). They can operate only in closed-loop configuration and their output voltage pulses are with variable frequency and variable filling factor. This switching operation principle is well known therefore it not will be presented here.

In the Digital Control Systems laboratory several types of PWM inverter architectures for servomotor control systems development has been designed and implemented [1]. One of them is the SGS-L298-L6506 configuration converter for stepping and DC motors drive. This power module is in fact a specially conceived current-source PWM inverter built up around two main integrated circuits, the SGS-L298 and L6506 ICs (both manufactured by the SGS Thomson Co.), as shown in figure 1. SGS-L298 is a power module embedding 8 bipolar transistor switches in a two H-bridge configuration [2, 3]. The maximal supply voltage of the circuit is $V_s=46V$, with a load current of $I_L=4A$. All the input signals of the L298 integrated circuit are TTL compatible, two outputs allow the current measurement in the motor phases, and each bridge is controlled with separate enabling signals.

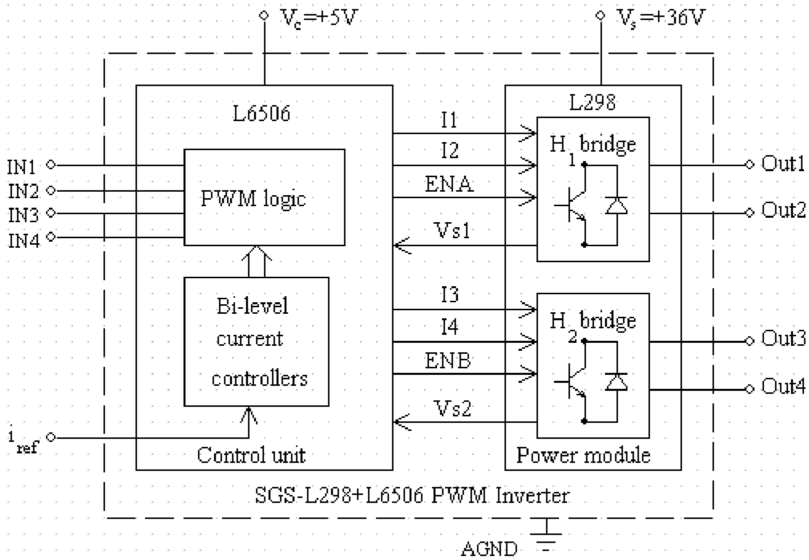

Fig. 1. The block diagram of the current-source PWM inverter unit

Because the circuit does not contain the necessary suppressing diodes connected in parallel with the power switches, it is recommended the utilization of the SGS-L6210 circuit which embeds 8 Schottky power diodes [3]. The L298 power module will be driven by the SGS-6506 current controller circuit which allows the desired PWM frequency setting by using an externally connected *RC* oscillator circuit [4]. The final result of the above mentioned circuit's interconnection is a powerful and versatile PWM inverter unit suitable to drive a wide range of servomotors (both stepper and dc.) with a maximal supply voltage of *46V* and *4A* load current. The general view of the current-source asynchronous (bang-bang) PWM converter module is shown in figure 2.

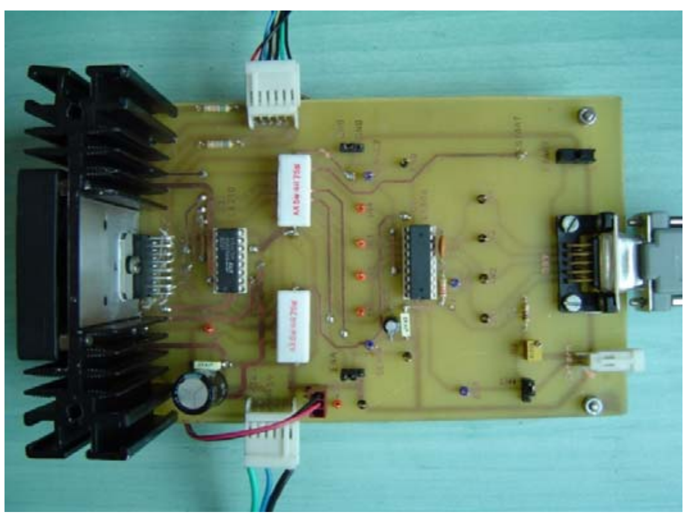

Fig. 2. The laboratory prototype PWM inverter unit

By using the on-board switches of the converter it is enabled the full drive of a two-phase bipolar stepping motor or two stand-alone dc motors; it is possible to control the PWM inverter operation via the PC's standard parallel port or by a D/A interface board which can set the current levels in the motor phases.

The above presented current-source PWM converter architecture can be substantially improved if it is used the specially conceived L6023 power module manufactured by the same SGS Thomson Co (fig. 3).

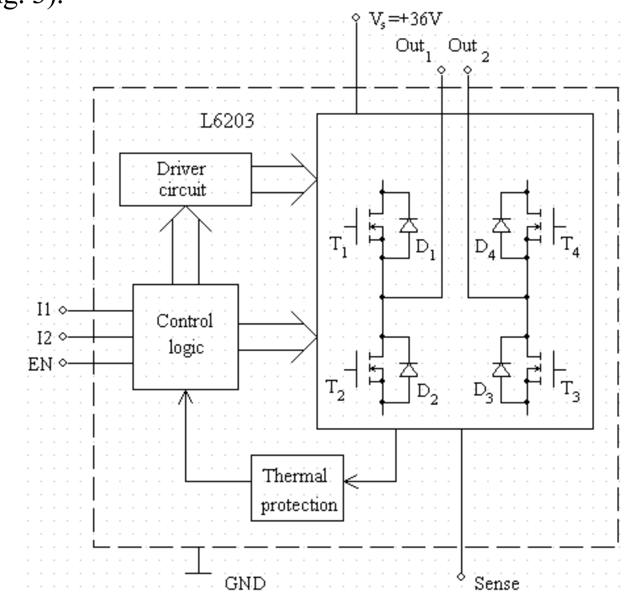

Fig. 3. The block diagram of the SGS-L6203 circuit

This is a classical H bridge configuration circuit built up with DMOS type power transistors also integrating into the chip the 4 suppressing power diodes. The maximal supply voltage of the L6203 circuit is $V_s=42V$, with a maximal load current of $I_L=5A$. All the input control signals of the IC are TTL compatible, allowing full compatibility with digital control systems [3, 4]. The *EN* pin it is used to control the on/off operation mode of the module and *Sense* for current measurement. Additionally, L6203 it is provided with a thermal protection circuit which switches off the entire module in case of the chip internal temperature reaches an imposed limit. By using this versatile power electronic module the PWM inverter unit from figure 1 can be transformed as is expressed in figure 4.

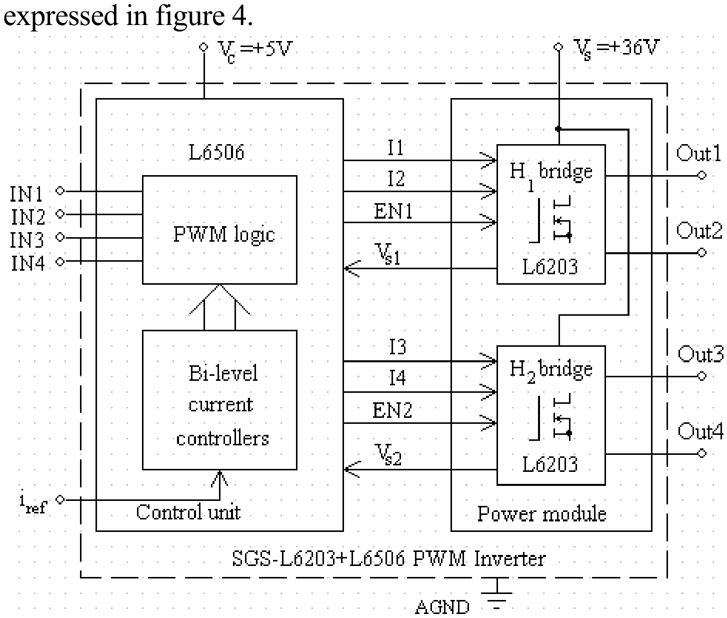

Fig. 4. The block diagram of the L6203+L6506 PWM inverter unit

The result is a reliable and versatile current-source asynchronous PWM inverter module which will be connected then to two-phase hybrid stepping motor phases (fig. 5).

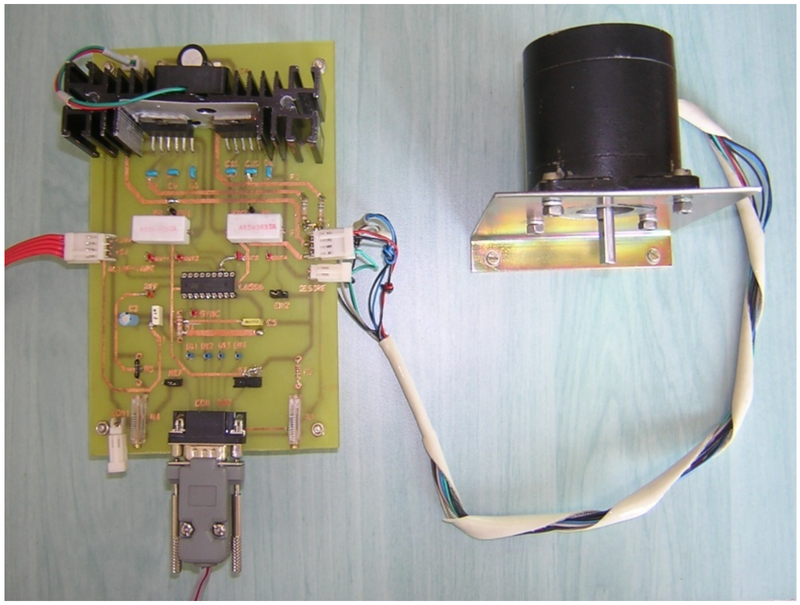

Fig. 5. The PWM converter interconnected with the stepping motor phases

Figure 6 evidences the basic architecture of the PWM SGS-L6203 inverter. This is an asynchronous (bang-bang) current source PWM inverter which reproduces with high fidelity in the motor phases the reference signals generated via the two analog output channels DA_0 and DA_1 of an adequate data acquisition board. The block diagram of the power converter from figure 15 outlines that the main elements of this inverter are the two *H*-bridge units built up by using the L6203 power module ICs [5].

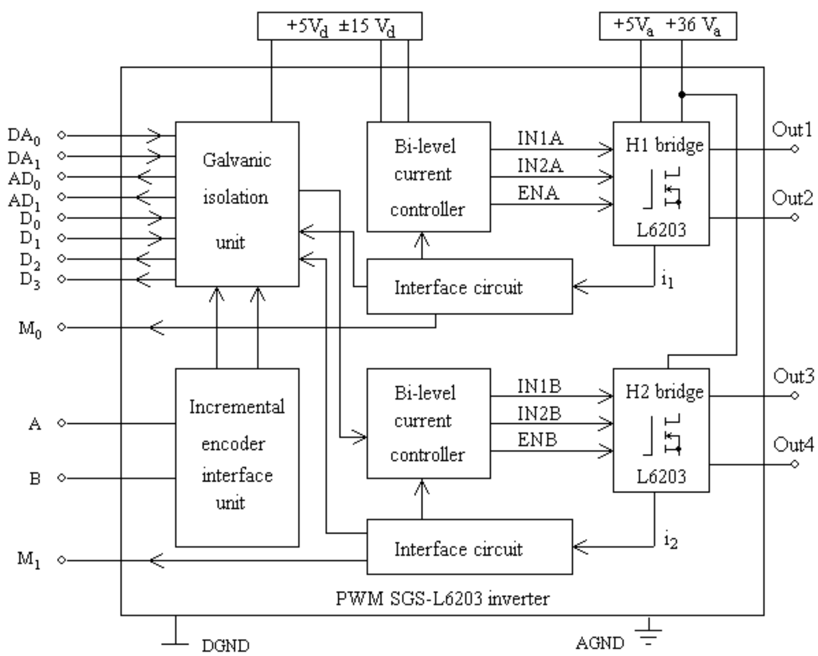

Fig. 6. The block diagram of current-source PWM inverter

The two phase currents of the stepping motor are measured by using two LEM-35-type current sensors which also serve as a galvanic isolation modules of the two acquired analog signals. Other analog or digital signals are galvanic isolated via the adequate optically-coupled integrated circuits. Figure 7 and 8 shows the prototyped power module, respectively the general view of the entire PWM inverter unit.

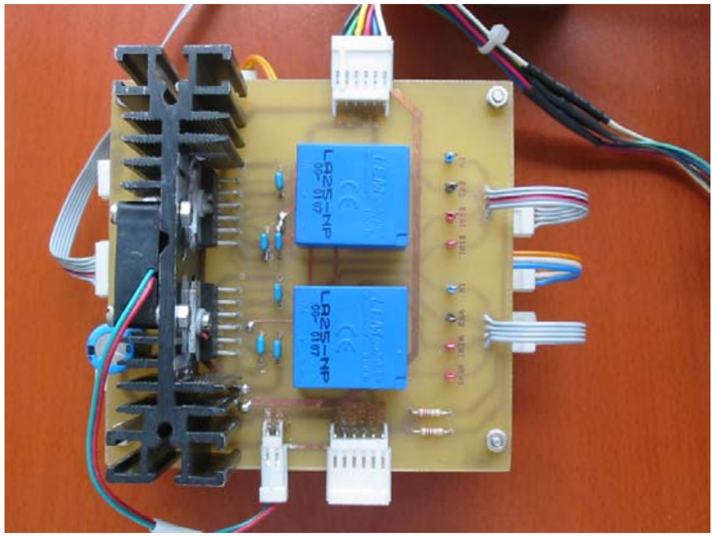

Fig. 7. The power module of current-source PWM inverter

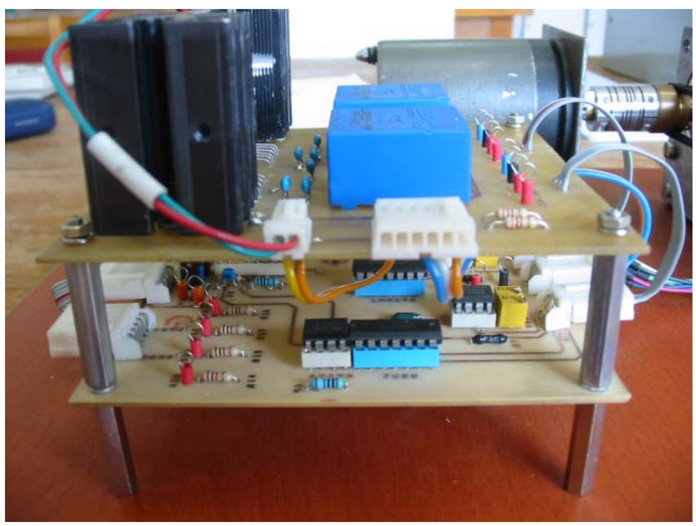

Fig. 8. The general view of the current-source PWM inverter

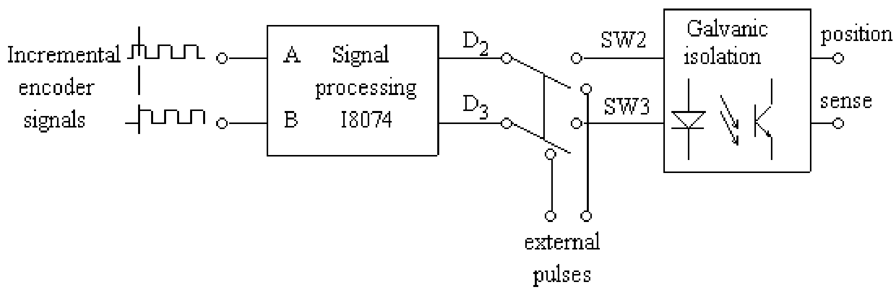

Fig. 9. Data acquisition of the incremental encoder signals

In figure 9 it is presented the block diagram of the data acquisition circuit connected to the TIRO-1000 incremental encoder. There the pulses generated via the two output channels of the encoder are processed by using the I8074 integrated circuit, which is a specially conceived IC for incremental encoder interface purposes. The obtained position and sense information are galvanic isolated with photodiode-phototransistor couples.

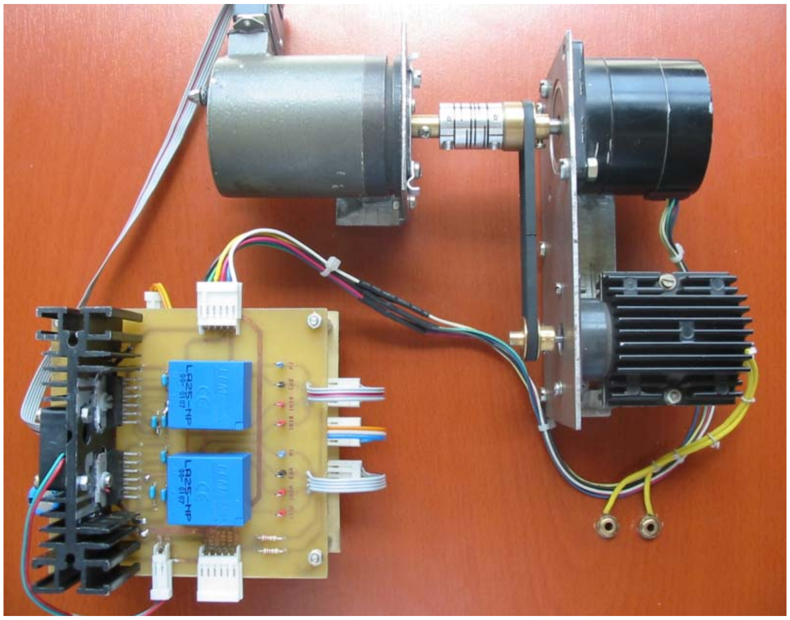

Fig. 10. The general view of stepping motor interconnected with the PWM inverter the incremental encoder and a DC motor-based load

Finally, in figure 10 it can be observed that in the laboratory-prototype setup the permanent magnet hybrid stepping motor it is connected to the PWM power converter module, the TIRO-100 incremental encoder and as a mechanical load it is used a DC servomotor.

2.2. SERVOMOTOR-BASED ELECTRICAL DRIVE SYSTEMS DEVELOPMENT AND IMPLEMENTATION

The development and implementation of the digital servo-control systems is one of the major goals of the research activities in Digital Control Systems laboratory. There the main efforts are focused on the incremental motion servo-systems experimentation having as actuator various types of stepping motors, or on DC motors-based servo control systems development. The open-loop servomotor control systems represents inexpensive and easy to implement solutions in automation applications where do not required high level the dynamic performances achievement. Therefore, from the performance/cost ratio point of view such digital control architectures often can be assumed as ideal solutions in a large scale of industrial applications and developments.

In order to support the above expressed theoretical remarks, in figure 11 it is presented the block diagram of personal computer-based open-loop incremental motion system where the actuator is two-phase hybrid stepping motor (HSM). In this hardware configuration the PC communicates via its standard parallel port (LPT1) with the process. The digital control signals are galvanic isolated from the power converter unit module which feeds the stepping motor phases. There the driver motor has the following nominal parameters: $U_N=24V$, $I_N=1A$, $\theta_s=1.8^\circ$, $M_N=0.2Nm$, and $z_r=50$.

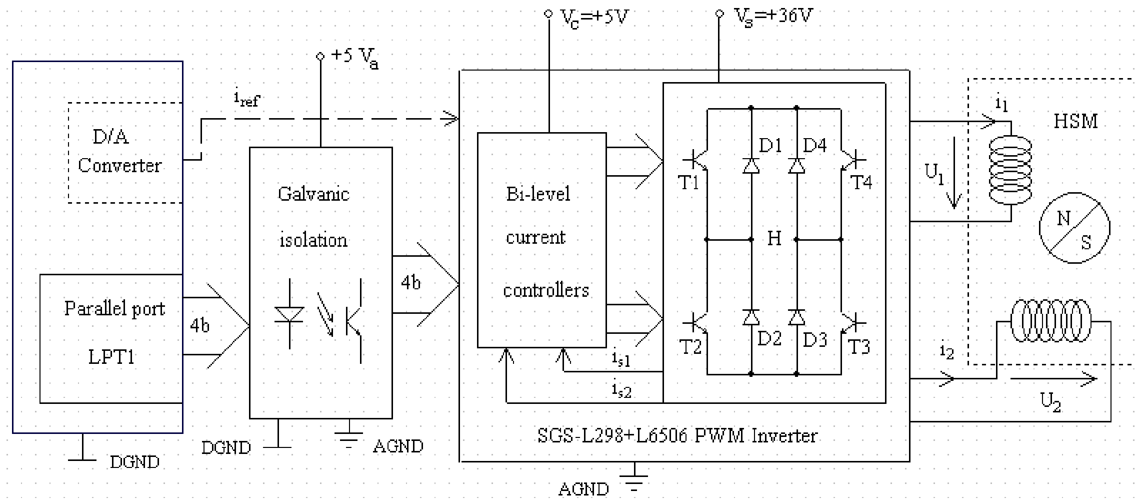

Fig. 11. The block diagram of a PC-based open-loop servo control system

The general view of the PC-based open-loop servomotor control system is shown in figure 12.

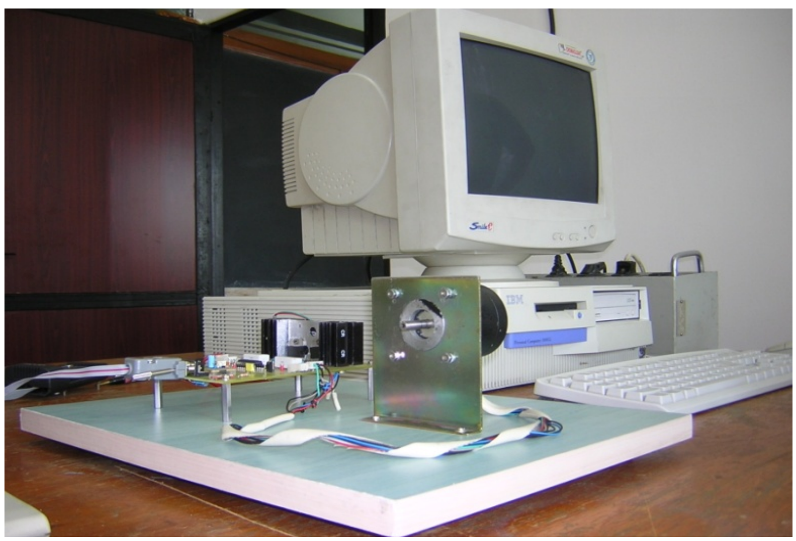

Fig. 12. The general view of the PC-based open-loop servomotor control system

As it is well known, closed-loop servo control systems provides higher dynamic performances (fast response, low steady-state error, low output magnitude oscillations, reduced override, etc.), therefore they are wide range utilized systems in demanding industrial applications and high-performance process control. The development and implementation strategy of such a closed-loop control system can be followed conveniently by choosing as example a servo system where the actuator is a permanent magnet hybrid stepping motor (PMSM). For this reason it is considered the block diagram form figure 13 [4].

In the given example the PMSM servomotor it is controlled by using a PC-based digital system. There the basic hardware architecture of the personal computer it has been extended with the powerful DAS-1600 data acquisition board connected to the open-access ISA-BUS standard bus. The digital/analog interface generates the stepping motor control signals as follows. The two output analog channels DA_0 and DA_1 of the DAS-1600 board generates the two motor phase reference signals i_1 and i_2 as shown below in figure 14.

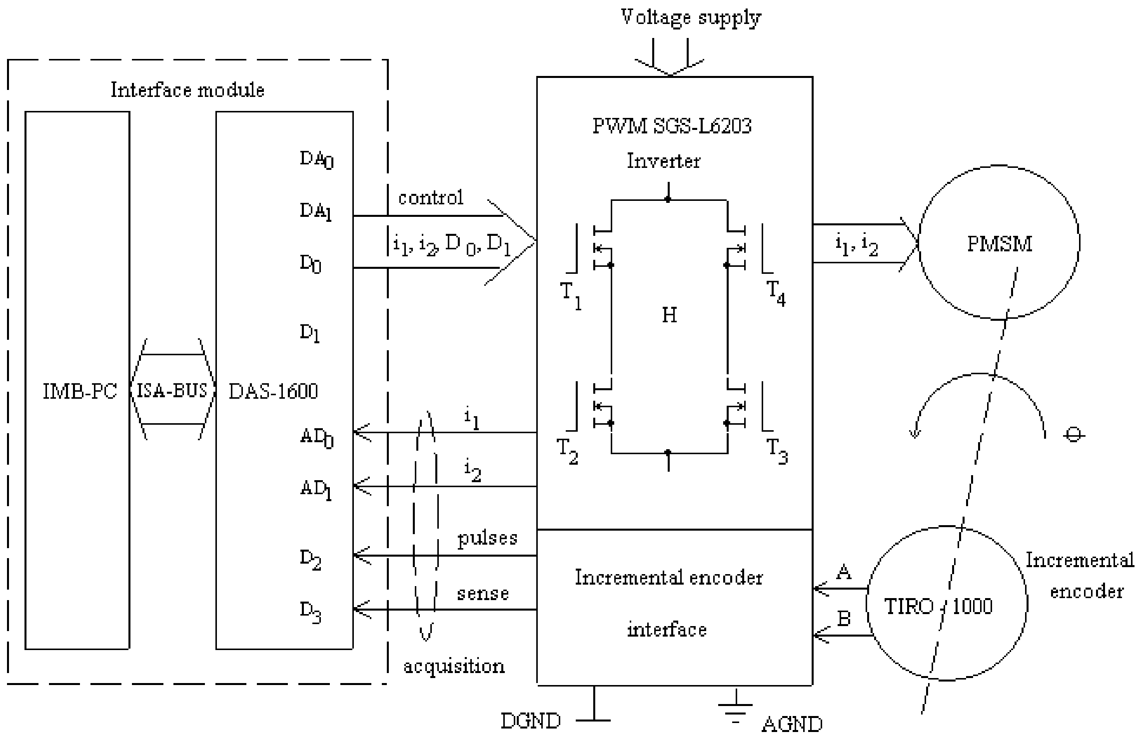

Fig. 13. The block diagram of a closed-loop stepping motor control system

As it can be observed from the figure, this is a two-phase bipolar hybrid stepping motor supplied with two sinusoidal waveforms delayed with each other by $\pi/2$ radians.

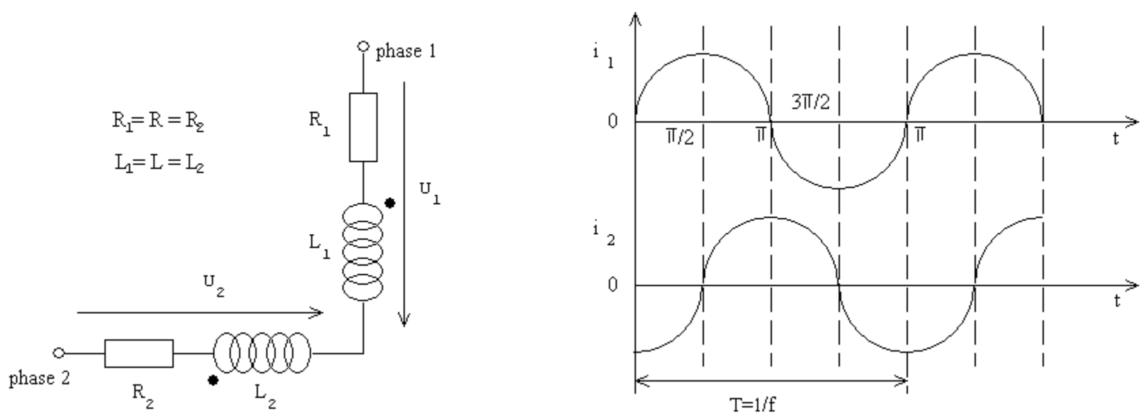

Fig. 14. The stepping motor phases supply with sinusoidal reference waveforms

Two digital output lines (D_0 and D_1) controls the on/off operation mode of the PWM converter unit *H* bridges. The stepping motor's rotor is mechanically coupled with a TIRO-1000-type incremental encoder. It means that it is possible to close two feedback loops by measuring both the angular position and velocity of the stepping motor. Therefore by using the D_3 and D_4 input bits of the data acquisition board it will be counted the number of the pulses generated by the incremental encoder (equal with the motor steps performed) and the frequency of these pulses (proportional with the rotor velocity), respectively the rotation sense of the motor. At the same time, via the analog input channels AD_0 and AD_1 are measured the motor phase currents i_1 and i_2 [5].

Fig. 15. The general view of the stepping motor-based closed-loop servo control system

The general view of the laboratory prototype stepping motor-based closed-loop servo control system is shown in figure 15.

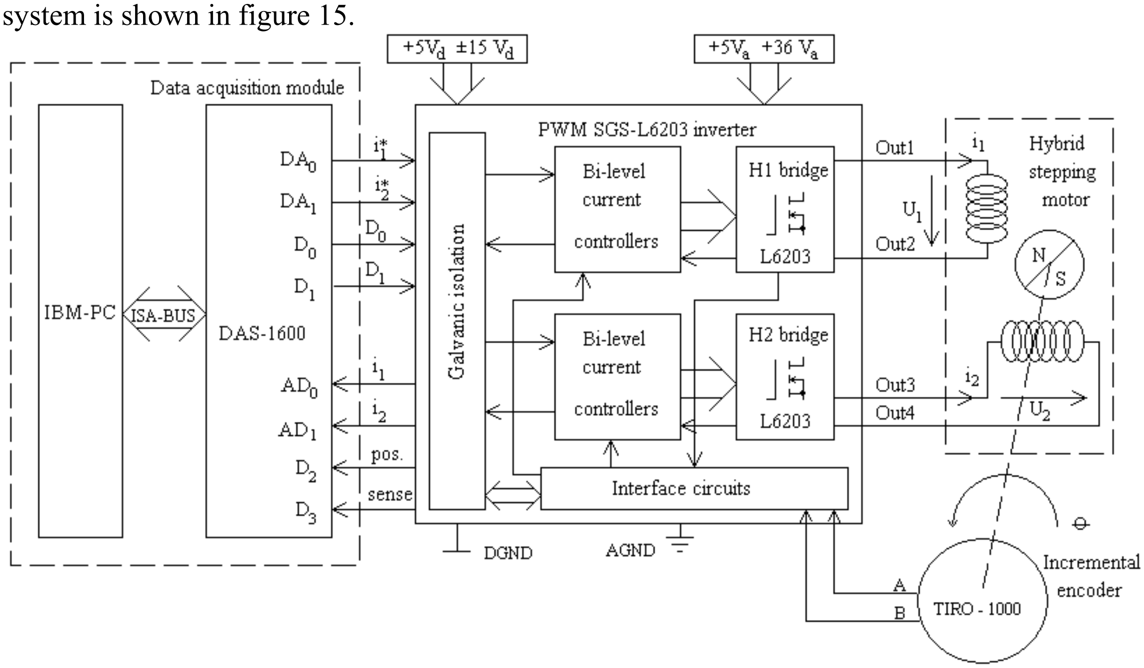

Fig. 16. The detailed block diagram of a closed-loop stepping motor control system

A detailed block diagram of this system it is given in figure 16.

By using microcontroller-based digital architectures it is possible to develop low price and reliable position control systems suitable for a large scale of industrial applications. In the followings it is presented an example how it was implemented in the Digital Control Systems laboratory a PIC16F877-type microcontroller-based stepper motor control system for open-loop applications [4, 5].

There it is considered a low-power four phase MSDA020G01-type stepper motor manufactured by the Sankya Co. The motor winding's arrangement of this servomotor is presented in figure 17. This micro motor has two stator windings each divided by two equal parts, and supplied from a voltage source of 5V. The obtained four stator phases will be connected to electronic switches and feed by positive voltage pulses, as shown in figure 18. This stepper motor operation principle is well known from the scientific literature, will not be discussed here.

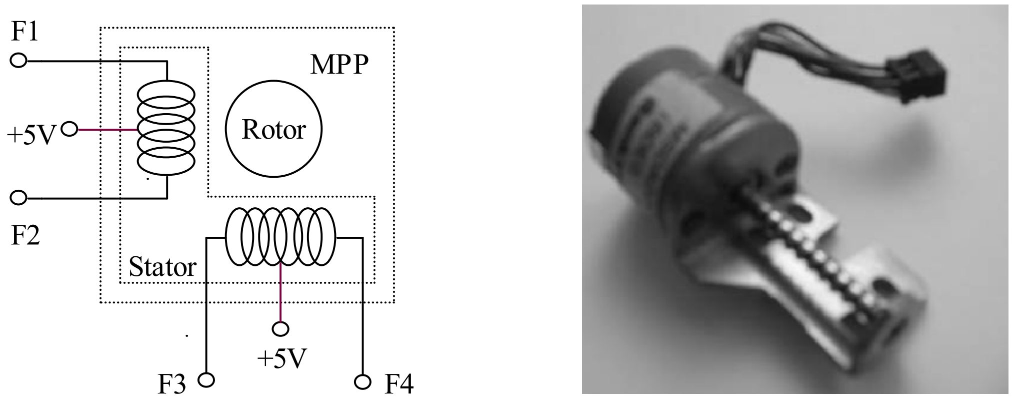

Fig. 17. The motor winding's arrangement and the motor's general view [5]

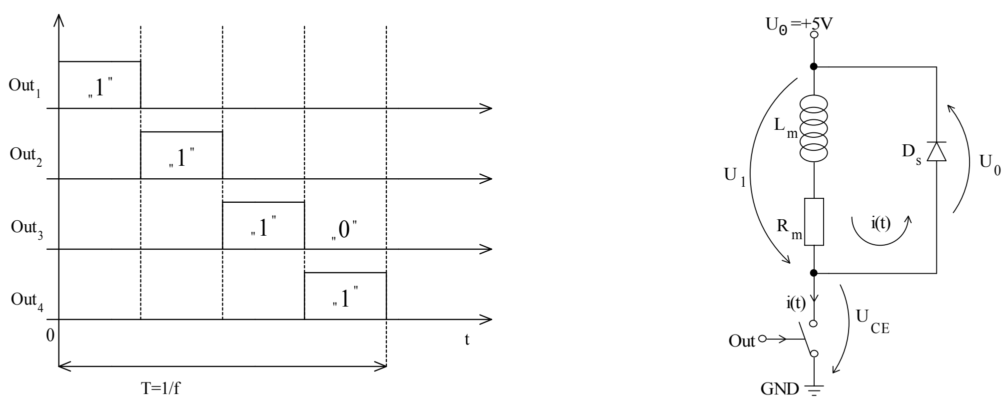

Fig. 18. The stepper motor operation principle

Because the PIC16F877 microcontroller is a single-chip computer without any interfaces for data introduction or program task supervising monitor, in the first step of the development efforts it is necessary to design and implement the microcontroller-based digital control system architecture with the adequate interface circuits. For this reason the development system shown in the block diagram from figure 19 has been proposed.

For the motor drive control tasks design and development the PIC Simulator software development toolkit has been used. In figure 20 is shown the main window of this application which is a user friendly graphical interface. The PIC Simulator IDE is a powerful tool which provides the full features of an emulator, assembler, basic compiler, disassemble and debugger. It has additional features such as FLASH program memory editor, powerful PIC basic compiler, and variable simulation rate. The program also helps the user to view and control the internal microcontroller architecture.

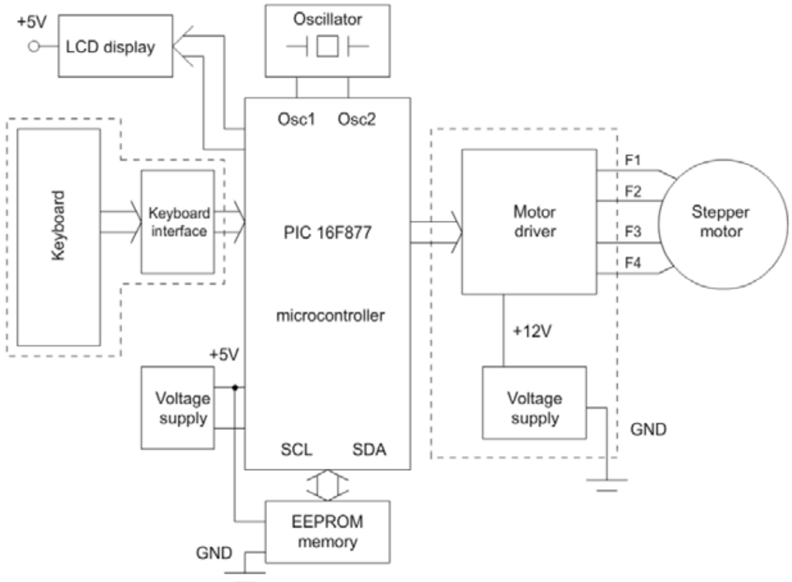

Fig. 19. Microcontroller-based stepping motor control system block diagram [5]

There the microcontroller is interconnected with input/output interfaces to communicate with its external environment (keyboard with push button-array, LCD display, LED display matrix, relays, etc.), respectively with the adequate stepper motor drive electronic converter.

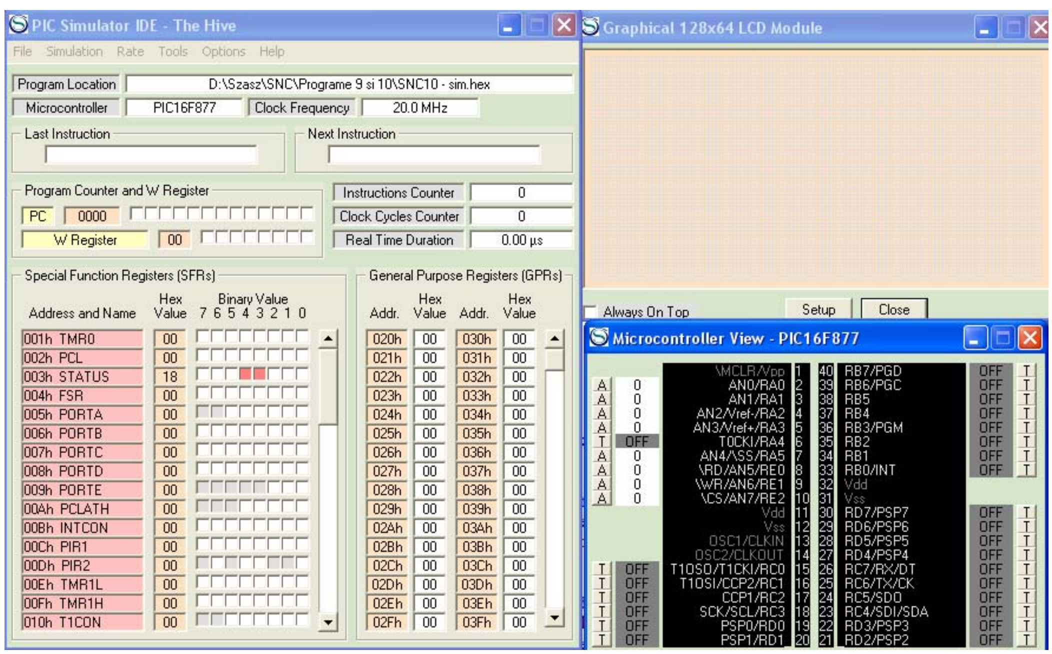

Fig. 20. The PIC Simulator IDE software development toolkit

Additionally, it is available a breakpoints manager, PC's serial communication, supports external simulation modules and extensive program options, and it is bounded with signal generator simulation tools along with an oscilloscope. Therefore this simulation toolkit is easy to operate and it is fully user-friend.

2.3. ELECTRICAL DRIVES DIRECT DIGITAL CONTROL SYSTEMS DESIGN AND IMPLEMENTATION

2.3.1. General purpose computer-based direct digital control systems development and implementation.

According to a general rule definition, a personal computer (PC) is a general purpose computer designed for individual utilization built up upon microprocessor-based hardware architecture whose size and capabilities allow it to be operated directly by an end user. As it is well known, nowadays personal computers are ubiquitous in our everyday life, being used in a wide range of human activities and purposes. Becoming almost indispensable issues of the daily life, they are very common devices in communication, information processing, or data exchange applications. Mainly, the personal computer term embeds two important categories: desktop replacement computers and laptop computers. Desktop computers provide the full capabilities of a powerful microcomputer while remaining mobile. Because of their increased size, this category of microcomputer (usually built up around a single microprocessor chip configuration) includes powerful hardware components (memory storage capability, input/output communication ports, interfaces, graphics card, etc.) and a larger monitor display, mostly without battery capacity. A laptop is defined as a small personal computer designed mainly for portability. They are provided with miniaturized hardware modules, where in most of cases the serial and parallel ports, sound channels or graphics card are integrated into a single unit. One of the most important behavior of a laptop computer is that contain high capacity batteries, enhancing portability. It means that extensive periods of time the device it is powered by the battery pack in a stand-alone operation mode of the computer. Due to the size and configuration of components the laptops relatively little can be done to upgrade the computer hardware from its original design. This drawback it means that hardware upgrades either not manufacturer recommended for this computer category [6].

However, the personal computers hardware architecture has been developed around the general purpose microprocessors chip structure, as the central processing unit of the entire digital system. General purpose microprocessors (like Intel family processors) are VLSI circuits designed for data processing via arithmetic and logical operations. Because of the data processing criteria is primordial in case of the personal computers, their hardware configuration and software support has been developed according to this requirement. The rapid development of the computer industry has generated a relatively low price personal computer offer on the market, resulting wide range accessible product for a large scale of various users worldwide. This evolution also has aroused the interest of the customers from the industrial applications area, which quickly discovers that a personal computer equipped with the adequate input/output interface board, can be transformed easily into a powerful signal processing computer very useful for industrial control applications as well. A personal computer is able to be equipped with several extension modules for different application purposes

There are on the market a wide range of companies involved in data acquisition board's development and manufacturing. In the Digital Control Systems laboratory has been used products manufactured by the Keithley MetraByte Co. The DAS-1600 data acquisition board is one of the most representative products of the Keithley MetraByte Co. [7]. This is a high speed analog/digital interface for IBM/PC/XT/AT and compatible personal computers which once has been connected to the bus system transforms the PC into a very powerful and versatile signal processing device (fig. 21). DAS-1600 allows the analog and digital signals acquisition from processes, events count and monitoring, and the generation of reference signals. The simplified block diagram of the board is presented in figure 22.

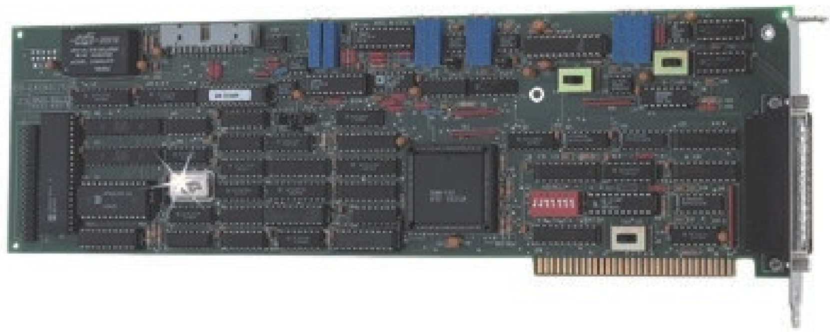

Fig. 21. General view of the DAS-1600 data acquisition board

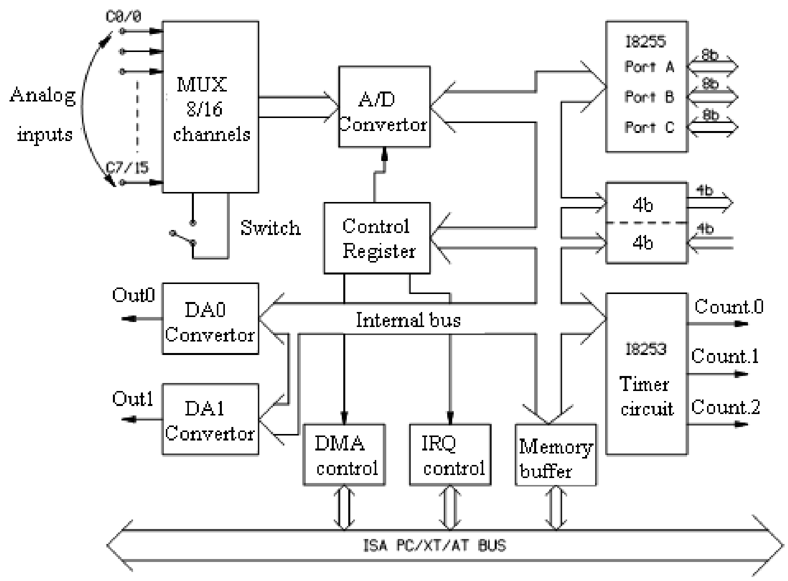

Fig. 22. The block diagram of the DAS-1600 data acquisition board

The module offers 8 differential inputs or 16 "single ended" analog inputs with a 12bit resolution A/D conversion. The acquired signals level can be settled into unipolar (0 ÷ 5V, 0 ÷ 10V) or bipolar (-5 ÷ +5V, -10 ÷ +10V) modes by using the configuration switches on the board. Analog signals also can be generated via the two 12bit resolution D/A channels. At the same time DAS-1600 can generate timing signals in the domain of 2.5NHz ÷ 1 pulse/hour and count various external events by using its 3 integrated 16 bit resolution down count registers. The maximal speed of the board is 100.000 samples/s by using its internal 10MHz system clock. The digital signals can be transferred via 32bits, 24 from these are generated by the embedded PPI-I8255 parallel interface standard circuit [7].

Keithley MetraByte Co. delivers the DAS-1600 board with a powerful software toolkit named ASO-1600 [8]. This package contains the *VI.exe* and *MDAS1600.exe* driver modules which controls the data acquisition module, tests its proper operation, the analog input/output channels calibration, or to display the result of the *D/A* or *A/D* conversions. ASO-1600 also embeds a collection of driver tasks named "Function Call Driver" for programming purposed in high-level programming environments like *Pascal, C++, Fortran*, or *Visual Basic* both in versions under MS-DOS or Windows operation systems. By using the strategy of equipping with adequate extension boards, practically the data processing personal computer becomes a signal processing digital system, very attractive from the performance/expenses rate point of view in many industrial applications.

2.3.2. Microcontroller-based direct digital control systems development and implementation

According to a general rule definition, the microcontroller is a specialized microprocessor used mostly in dedicated control systems to perform a specific program task. One of the most important behaviors of this processor type is that embeds into a single chip structure not only the central processing unit (CPU), but also ROM and RAM memory blocks, input/output ports, counter/timer circuits, analog/digital converters, pulse width modulation (PWM) ports, or other specific interface units for industrial processes control. Therefore, it can be considered that the microcontroller is in fact a specialized computer integrated into a single silicon chip [1, 9].

By using microcontroller-based digital architectures becomes possible to develop and implement relatively sophisticated computing systems, outstanding with its small sizes, low power consumption and low implementation prices as well. Hence, the microcontrollers are devices used with high success in a wide range of applications, such as: industrial process control (position, velocity, electromagnetic torque, pressure, light intensity, force and acceleration control, etc.), domestic applications (washing machine, fax, TV, mobile phone, video applications, musical instruments, microwave, etc.), office applications (printers, copiers, phone devices, etc.), in the automotive industry (combustion control, climate control, transmission control), military applications, etc. The microcontroller's small volume occupied, their low power consumption, very low cost per unit, high processing speed, and not at least their high flexibility in programming and upgrading issues, offers to the microcontrollers important advantages against other microprocessor-based digital control systems used for industrial processes control [9, 10].

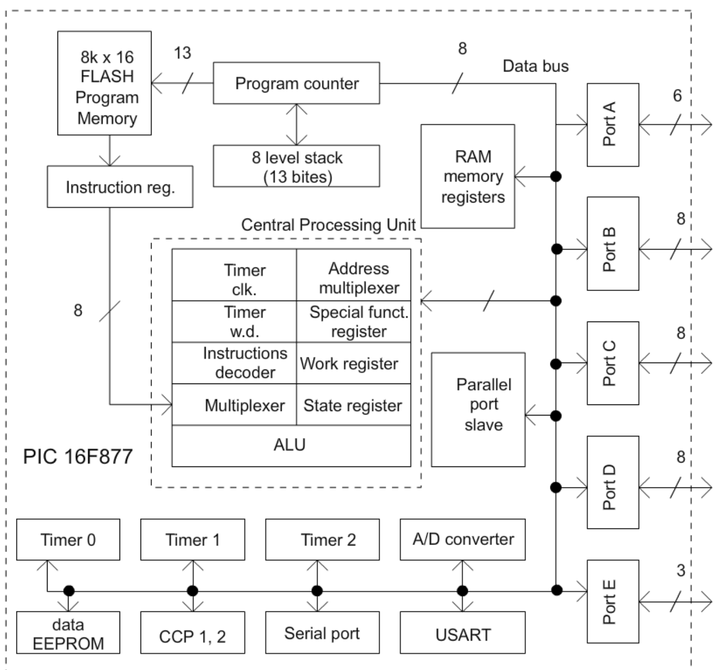

Fig. 23. Block diagram of the PIC16F877 microcontroller

In the Digital Control Systems laboratory the first used microcontrollers were the *PIC16F7x* family (Programmable Intelligent Computer 16F87x) manufactured by the Microchip Technology Inc. This family also includes PIC16F873, PIC16F874 and PIC16F876, a more recent chip being PIC16F877. Among the large-scale products of this company the PIC16F877 chip is an 8 bit microcontroller developed in CMOS FLASH technology used with high success in industrial applications because their remarkable performances and facilities provided [9, 10]. The block diagram of this microcontroller is presented in figure 23.

Considering the above introduced technical characteristics, it can be stated that the PIC 16F877 it is a high performance single-chip computing unit. In order to develop assembly language software programs for various industrial process control applications, the PIC 16F877 a large scale of software products can be utilized. One of these is the MPLAB IDE Software development product, as a Windows-type application. This include into a single software package an editor in assembly or C language, assembler, programs debugger, a PIC operation simulator, and an emulator-type application [9, 10]. Such a software resource looks powerful enough for development of a various type complex microcontroller-based applications and process control tasks.

There are in the Digital Control Systems laboratory wide ranges of microcontrollers-based hardware systems well suited for various electrical drive control systems development and implementation. Among these one of the most versatile is the BigPIC6 hardware development system shown in figure 24. This is a powerful and versatile development board for programming and experimenting with Microchip PIC18Fxx controllers, including on-board programmer with *mikroICD* support providing an interface between the microcontroller and a personal computer. The central processing unit of this system (a microcontroller from the PIC18Fxx family) is rich interfaced with a large set of on-board hardware modules, such as alphanumeric 2x16 LCD display, 128x64 graphic LCD display, or an I/O port expander, allowing easy to simulate operation of the target device. The BigPIC6 also provides an USB 2.0 programmer, two RS-232 ports (RS-232A and RS-232B) for serial communication, serial EPROM using I^2C communication, a 10 bit A/D converter, DS1829 temperature sensor, real-time clock, 67 LED's to indicate the input/output pins' logic state, a keyboard with 67 push buttons, a navigation menu keypad, and a set of nine 10-pin connectors connected to the microcontroller I/O ports [11].

Fig. 24. The BigPIC6 hardware development system

The enumerated rich hardware resources allow a sufficient freedom to the designer to develop and prototype a large set of real-time control algorithms for a given application. At the same time, the BigPIC6 development board can be conveniently programmed in *MicroPascal* source code, allowing a high level of freedom for the software implementation and real-time algorithms prototyping. For this purpose also a large set of prewritten and implemented controller algorithms are stored into a specific library toolkit. Then the elaborated algorithm control algorithms can be downloaded into the development board's memory by using the *mikroProg Suite for PIC* program. This software tool it has been intended for programming PIC and dsPIC microcontrollers from Microchip Co. It is a clear and easy-to-use program, being an adequate interface to the hardware module, providing basic information about the selected microcontroller unit, voltage and variables monitoring.

2.3.3. Digital signal processor-based control systems development and implementation.

The Digital Signal Processor-based (DSP) control systems development and implementation has been unfolded in the framework of the postdoctoral study at the Tokyo University of Technologies (TUAT), where the main research topic it was linear drives digital control systems development and implementation. As it is well known, the linear motors are direct drive actuators without the intervention of any motion conversion mechanical system. Contrasted with circular motion of a conventional electric motor, a linear motor is an electromechanical device that converts energy (electricity, air or liquid) to create motion in a straight line. It is easy to understand their operation mode if it is considered the general case of an unwrapped classical rotary motor. It is also well known that in the rotation movement a rotary motor re-uses the same magnetic pole configuration faces again and again, instead the linear electric motors where the magnetic field structure is physically repeated across the length of the actuator. Since the mover of the motor changes its position in a linear fashion to begin with, no mechanical systems is required to convert rotary motion to linear, which property constitutes one of the most important advantages of this actuator. Hence, electric linear motors are the perfect solution when it needed a simple and safe movement with accurate and smooth motion control. Moreover, electric linear motors-based systems has long lifetime with low maintenance costs, being a quiet and clean actuator. Additionally they offer accurate and high resolution movement, fast response, and high acceleration rates. Usually the maximum speed of a linear motor it is limited only by the switching speed of the control electronics. This type of actuator it is well suited to be integrated into sophisticated digital control systems, offering precise position feedback and accurate velocity control.

Obviously, the important advantages of linear electric motors can be exploited in an adequate manner only if the most appropriate digital control system it is designed and implemented for its drive. As it is well known, the DSP is a specialized microprocessor with a hardware architecture optimized for the mathematical operational needs of digital signal processing (especially time domain quantification, signal amplitude quantification, and analog/digital conversion). Therefore, the DSP is a wide range used processor type especially in applications where the signal processing algorithms require a large number of mathematical operations to be performed quickly and repeatedly on a series of a low number of data samples. They are built on a Harvard architecture where separate program and data memories are used, and concurrent access on multiple data buses is allowed. Common DSP features are the specialized instruction set, multiple memory banks and buses, data path configured for DSP, specialized addressing modes and execution control, specialized interface circuits for DSPs. The top model DSPs runs with clock speeds around 1-2 GHz, implements separate instruction and data caches, and are capable of as many as 8000 MIPS processing speeds in fixed-point or floating point arithmetic. With their specific hardware architecture DSPs performs complex data processing tasks that are not possible with analog circuitry, providing better signal quality and repeatable processing performance. At the same time outstands with their high flexibility (program tasks modification, upgrading software resources, etc.) performing a lower cost digital signal processing for equivalent performance. Reproducibility (the performance of a DSP can be reproduced precisely from one unit to another), reliability (the DSP hardware does not deteriorate with age), and complexity allowing sophisticated applications are another strengths of this processor type. Among the disadvantages of this processor type it must be mentioned that the need for several digital/analog and analog/digital converters makes it uneconomical for simple applications, additionally DSP techniques are limited to low-bandwidth signal applications. There it must be also mentioned that they requires longer hardware and software design time and problems of finite word error must occurs.

One of the most important DSP producer company is the Texas Instruments Co. with its worldwide well known TMS320Cx family series. The TMS320Cx family consists of two types of single-chip DSPs: 16-bit fixed point and 32-bit floating point. These two main hardware architectures combine the flexibility of high-speed controllers and processing capability of array processors. They offer more adaptable approaches to traditional signal processing problems, such as filtering, error coding, or decoding, supporting complex operations that require parallel processing operations. The result is a powerful and cost-effectiveness high-speed performance, flexible and parallel architecture design processor family, very useful and versatile especially in signal processing applications. Among these, the TMS320C5x family outstands as one of the most important Texas Instruments products. The simplified block diagram of a TMS320C5x processor core is presented in figure 25. As one of the last generation Texas Instruments DSP devices, TMS320C6x is the first chip to feature the *VelociTI*^{TM} technology with advanced very long instruction word (VLIW) architecture with a high degree of parallelism. This hardware configuration allows a performance of up to 1600 MIPS. The ‘C6x development tools include a Windows-based debugger, an assembler optimizer, and a new compiler [12, 13].

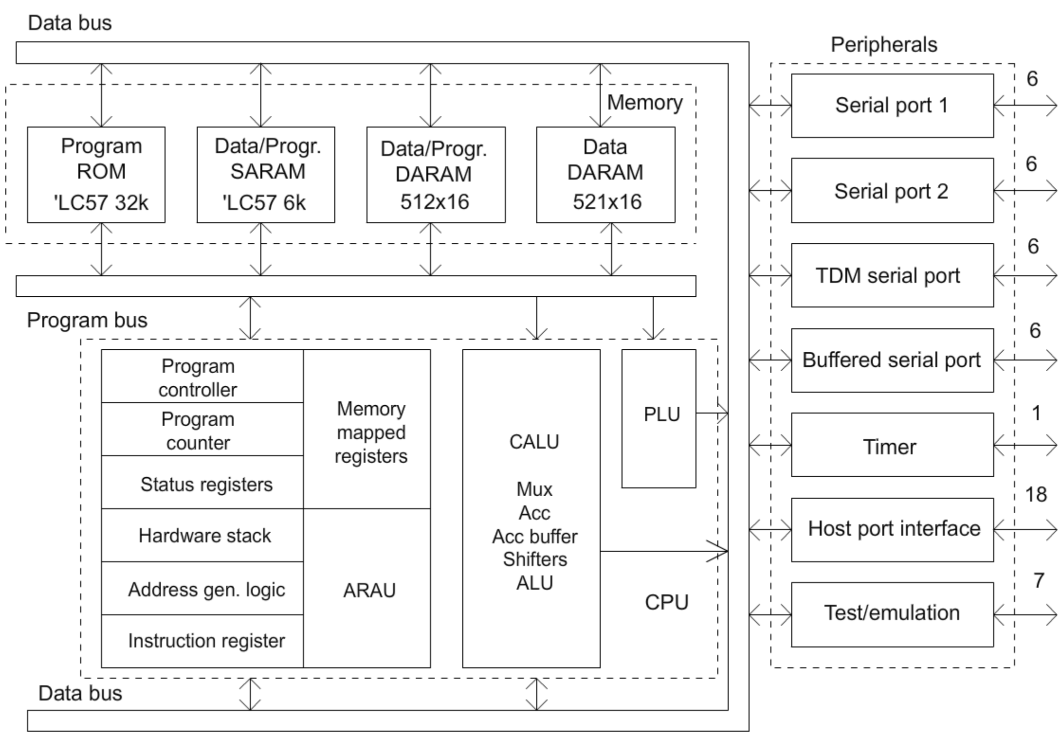

Fig. 43. The simplified block diagram of a TMS320C5x DSP core [12]

The key features of the TMS320C6x core are as follows: *VelociTI*^{TM} technology and VLIW architecture, CPU with 8 independent functional units (including two 16-bit multipliers with 32-bit results and 6 ALUs with 32-40-bit results), 32-32 bit registers, 5ns cycle time, 1600 MIPS speed, bit-field instructions, for channel direct memory access (DMA), 2 counter/timers, two multichannel serial ports, X4 phased-locked-loop (PLL) option, host-port interface (HPI), 1M-bit on-chip memory (divided into 2k by 256 bits of program memory and 64k bytes of data memory) [13].

However, DSPs are widely used devices in many industrial applications where real-time processing capabilities it is required (voice signal processing, audio production, digital cameras, music synthesis/effects, healthcare, servo control, image processing, signal filtering, military applications, digital cellular phones, satellite communications, security systems, etc.). What it is important to note here, is that DSP tasks requires attention to numeric fidelity, repetitive numeric computations, high memory bandwidth via array accesses, and real-time processing. A specially developed DSP-based digital control system which fully satisfies the above ranked all requirements and expectations for a linear synchronous motor real-time control has been developed at the Environmental and Symbiotic Production Systems Department lead by Prof.dr. Yoshio Kano, Graduate School of Bio-applications and Systems Engineering, Tokyo University of Technologies and Agriculture, as shown in figure 26.

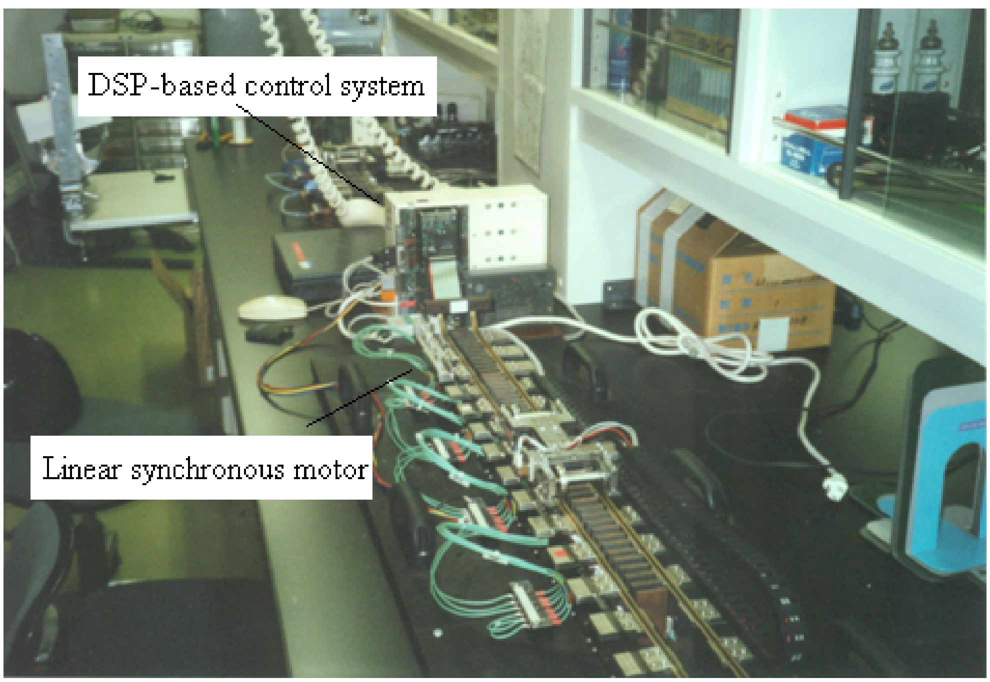

Fig. 26. DSP-based linear synchronous motor control system
(Department of Environmental and Symbiotic Production Systems, Graduate School of Bio-applications and Systems Engineering, TUAT, Japan)

There the main research tasks have been linked with the linear synchronous motor control algorithms development and implementation (acceleration/deceleration, velocity control, position control, etc.) by using a TMS320C4x 32-bit floating-point processor-based digital control system. The given actuator is a modularized linear synchronous motor, driven by a PWM converter, and provided with an incremental position encoder mounted across the length of the mover motion of.

2.3.4. Programmable logic controller-based digital systems development and implementation.

In actual stage of the microprocessor-based digital control systems development and implementation the general purpose microprocessors, the FPGA circuits, or the general purpose microcontrollers are wide range used hardware architectures for industrial processes control. However, nowadays a vast majority of industrial processes are controlled by using Programmable Logic Controllers (PLCs). These hardware structures are in fact a special type of computers which has been designed and manufactured to control industrial applications, being named as industrial computers [14, 15].

According to a general rule definition, the PLCs are logically programmed hardware units built up upon a microprocessor-based structure and used in electromechanical processes automation, with the major scope to perform switching, timing, or monitoring operations in industrial processes control. In other words, the PLC implements logical functions for process control by using specific program tasks. In fact it can be stated that the PLC-based systems has been designed to replace the relays-based automation systems in industrial applications. The major advantages of the PLCs over the electromagnetic relays-based automation systems consist in the followings [1]:

- the PLC-based systems has a very long operation lifetime (the electromagnetic relays are devices with a limited operation lifetime);
- exhibits a high reliability (the electromagnetic relays are unreliable devices);
- expresses high flexibility and versatility;
- low power consumption;
- low implementation expenses;
- low number of interconnections;
- the PLC-based systems can operate in pollutant industrial environments (corrosive environments, chemically pollutant environments, electromagnetic noises, etc.);
- any changes in programming PLC controllers are easily achieved, expressing a high degree of flexibility in industrial applications;
- the fault diagnosis is performed automatically;
- the PLCs are easy programmed an software upgraded;
- the PLCs can be interconnected with a wide range of peripheral devices (electrical motors, sensors, buttons and switches, measuring equipments and devices, hydro-pneumatic devices, etc.).

Among the disadvantages of the PLCs can be mentioned:

- in comparison with other digital control systems (for example the microcontrollers-based systems) the PLCs has a closed-structure hardware configuration;
- the main software packages of various PLC manufacturers are not compatible with each other.

The interconnection of PLCs in industrial processes is solved in an ingenious way. As shown in figure xx, each PLC communicates with its environment via a two screw terminals. One screw terminal is for input signals, and the other only for outputs. Both of them are galvanic isolated, and as shown in figure 27.a, allows the interconnection with a wide range of electrical devices and instruments (any type of switches, push-buttons, coils, electric motors, LEDs, hydro-pneumatic devices, etc). As a result, a PLC-based digital control system communicates with an industrial process via two main buses (fig. 27.b).

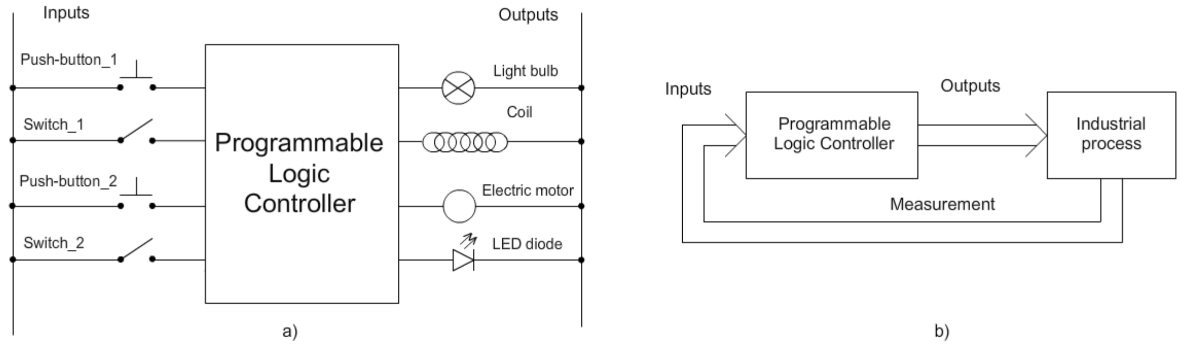

Fig. 27. The PLC interconnection with industrial processes

There are on the market a wide range of important PLC manufacturer companies. Among these one of the most important is the Schneider Electric Co., with its Twido PLC family series. In the Digital Control Systems laboratory it is available TWDLCAA40DRF PLC development set, as shown in figure 28.

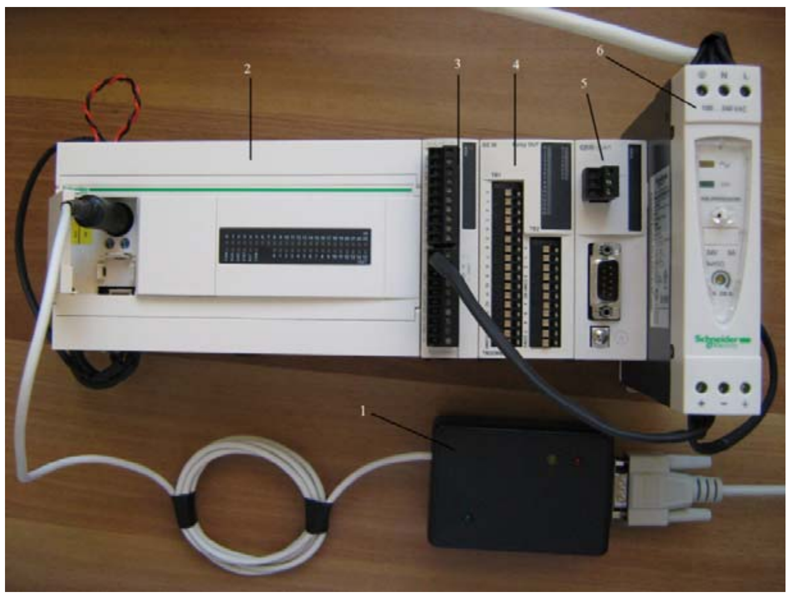

Fig. 28. The TWDLCAA40DRF PLC development setup

The hardware configuration shown in the figure includes the following basic modules:

- 1 - RS232/RS485 programming cable;
- 2 - TWDLCAA40DRF Programmable Logic Controller main unit, with 40 digital I/O communication lines;
- 3 - TWD AMM6HT analog input/output module (4 analog inputs and 2 analog outputs);
- 4 - TWD DDM24DRF digital input/output module with 24 input/output lines;
- 5 - CANopen module for network communication;
- 6 - ABL 8REM24030 power supply module;

The TWDLCAA40DRF PLC unit embeds one RS485 communication port, a LED display module to indicate the input/output lines state, 100-220V AC or 19,2-30V DC power supply connectors, 24 digital input lines, 14 relay outputs, and 2 transistor outputs. The main control unit it is supplied from the ABL 8REM24030 power module (110/220V/72W) which provides 24V output communication channels [14, 15].

The Schneider Electric Co. manufactured PLCs can be easily programmed by using the Ladder Logic graphical programming language with toolkits embedded into the Twido Suite software package. For example, it is considered the algebraic relation which implements the following logic function [1]:

$$f = f(x_1, x_2, x_3) = x_1 x_2 \overline{x_3} + x_1 \overline{x_2} x_3 + \overline{x_1 x_3} + \overline{x_2}\,. \tag{4.1}$$

The above expressed equation will be implemented in the Ladder Logic graphical programming language as shown in figure 29.

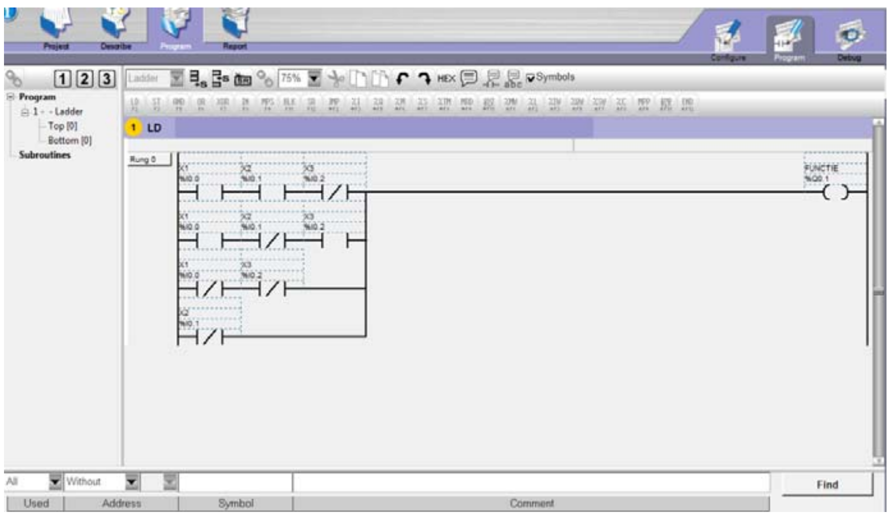

Fig. 29. Ladder Logic programming example

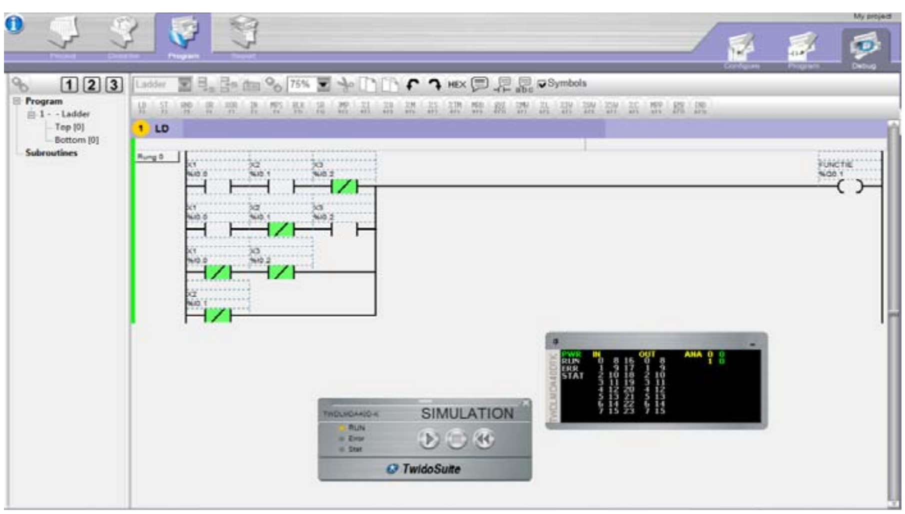

Fig. 30. Simulation of the implemented Ladder Logic program

An embedded simulation toolkit allows the graphical simulation of the implemented logical function (fig. 30).

2.3.5. FPGA processor-based digital systems development and implementation.

The FPGA (Field Programmable Gate Array) processors are VLSI circuits built inherently with massively parallel structures with a powerful hierarchy of customer reconfigurable interconnection networks. In particular, 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 [16, 17, 18]. All this is completed by seamless and efficient mapping of system functions and vast re-routing abilities supported by a programming flow that abstracts the hardware implementation details. Therefore, the FPGAs are frequently used in high complexity applications where hardware reconfigurable architectures are required, being easy to reprogrammed and versatile in complex algorithms implementation. They represents the ideal solution in process control where it is necessary the hardware configuration frequent modification as function of the user's needs [19, 20].

The FPGAs are manufactured as programmable arrays (programmable matrixes) with regularized, flexible, and reprogrammable hardware architectures named Configurable Logic Blocks (CLBs) or *CLB* units. These are interconnected into a matrix with powerful communication networks. The *CLB* blocks are surrounded on their four lattices with programmable input/output units (Input/Output Blocks) named generically *IOB* blocks. Beside the above, the processor also contains four *BlockRAM* memory blocks and four *DLL (Delay Locked-Loop*) units. The block diagram of an FPGA circuit is shown in figure 31.

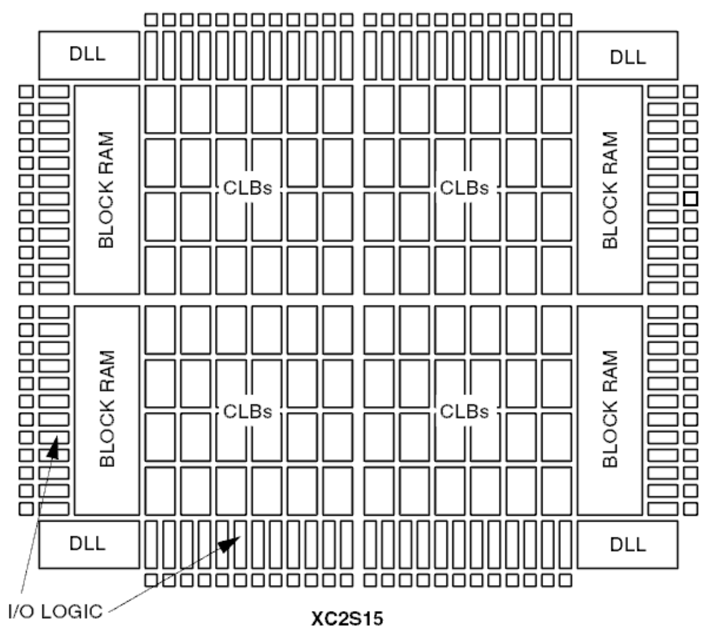

Fig. 31. The block diagram of an FPGA circuit [21]

The user will program the FPGA network as desired and configuration information will be loaded into the on-chip static memories. Circuit programming is possible without limitation, whenever the user wishes. The FPGA is capable to read its configuration even during its operation, by using serial communication with an external PROM memory (Master Serial mode) or the configuration data can be stored into an external unit (Slave Serial mode). The PC-based configuration of the FPGA processors is done by using the *JTAG* communication interface.

The flexible and regularized hardware architecture of the FPGA circuits organized into a two-dimensional *CLB* array it is ideally suited for parallel and distributed execution of the instructions inside the chip structure. This property makes that the FPGA processors operates at high speeds compared with other type processors with a very low sampling time. Table 1 presents a comparative estimation among the processing speed of the most important processor types currently available on the market.

	General purpose microprocessors	General purpose microcontrollers	Digital Signal Processor	FPGA processor
Sampling time	100 ms	1 ms	10 μs	100 ns

Table 1. Processors sampling time (processing speed)

It can be observed from the table that the FPGA processors operate with the fastest processing speeds, their sampling time could decrease below the 100ns limit. For this reason they are used especially in digital control systems with high switching frequencies requiring low processing times for real-time control purposes (power electronics, variable speed electrical drives, PWM modulation, etc.).

A typical application of the FPGA circuits is the variable speed electrical drives where a very short processing cycles it is required (signal acquisition, processing, reference signals generation). In those applications the FPGA processor fulfills the role of the digital controller, as is expressed in figure 32.

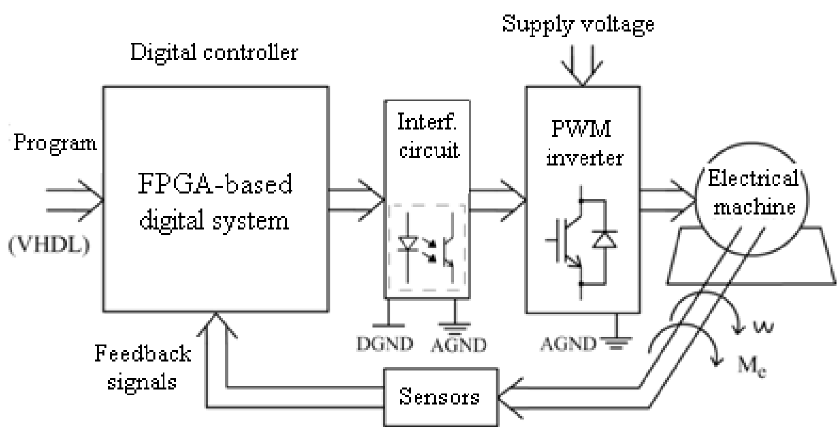

Fig. 32. FPGA-based electrical drive system

In a similar way, the FPGA processors can be utilized in a large scale of industrial processes control where it is necessary various type of physical magnitudes acquisition (position, velocity, electromagnetic torque, pressure, temperature, flow, light intensity, humidity, etc.),

In the Digital Control Systems laboratory there are equipped various types of FPGA processor-based digital control systems, ranging from the simplest to the most complex architectures. For example, the main role of an FPGA-based digital controller can be fulfilled with success by the *Digilent BasysBoard* development system. This is a Digilent Co. manufactured product and it is a Xilinx Spartan3E-100 FPGA circuit-based development platform. It is a cheap and relatively simple digital system designed to learn the user to work with FPGA processors and their programming with powerful CAD-type software toolkits.

Fig. 33. General view of the Digilent BasysBoard

All these hardware resources can be identified in figure 33 where a general view of the *Digilent BasysBoard* development system it is presented. In order facilitate the understanding of the above presented theoretical remarks, in figure 34 is shown a block diagram of the entire development system. There it can be observed that by using a 5-12VDC switch the development system can be supplied from *3.3VDC, 2.5VDC*, or *1.2VDC*. In the same way, the user can set the desired clock frequency: *25MHz, 50MHz*, or *100MHz*. Additionally the system also embeds 9kb *BlockRAM* memory, and the FPGA processor has integrated 4 18-bit on-chip multiplexers [22].

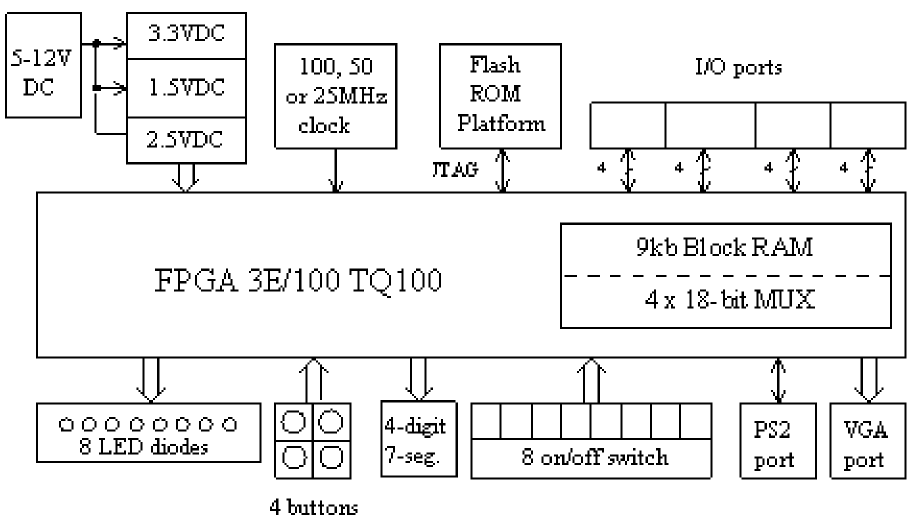

Fig. 34. The block diagram of the Digilent BasysBoard development system

The *Digilent BasysBoard* development system is compatible and works with all the versions of the *Xilinx ISE Tools* software toolkits. Programming these environments are very convenient and easy to assimilate by the users.

One other development system which can be used with success in industrial processes control is the *Spartan-3E Starter Kit Board* (fig. 35), specially designed to evidence the hardware facilities of the *XC3S500E Spartan-3E FPGA circuit*, manufactured by the Xilinx Co. [42].

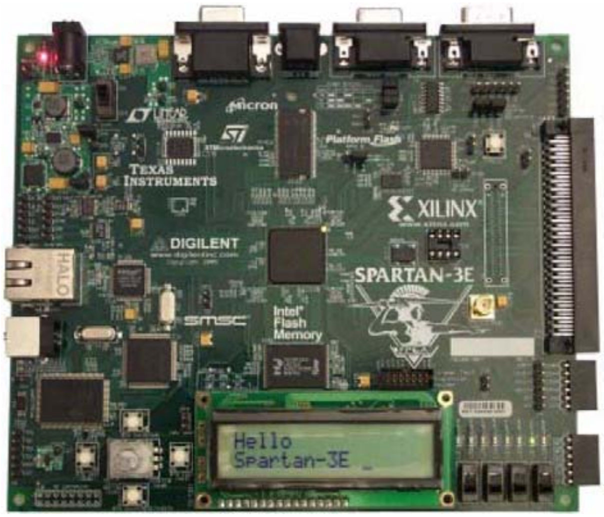

Fig. 35. The general view of the Spartan-3E Starter Kit Board [23]

Figure 36 presents the general view of Genesys Virtex-5 FPGA Development Board, as one of the most powerful Digilent Co. products. This is a complete, ready-to-use circuit development platform based on Xilinx Virtex 5 LX50T FPGA processor.

Fig. 36. The general view of the Genesys Virtex-5 FPGA Development Board

The Virtex5-LX50 T FPGA is optimized for high performance logic offering 1.7Mbits fast block RAM, 48 DSP slices, 6 phase-locked loops, 7200 slices (each containing 6 input LUTs and 8 Flop-Flops), 12 digital clock managers, 500MHz clock speed [24]. The board also includes the newest Adept USB2 system, automated board tests, virtual I/O and simplified user-date transfer facilities, real-time power supply monitoring, and two USB ports based on the Xilinx programming cable.

The above presented development boards are widely used in the Digital Control Systems laboratory for current-source PWM power electronic converters control, where high switching frequency are required. The basic principle of this control strategy is presented in the block diagram from figure 37.

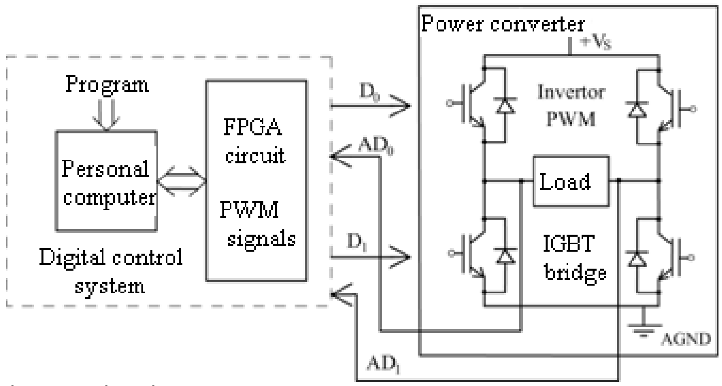

Fig. 37. FPGA-based PWM control of a H-bridge configuration PWM power electronic converter

In this example the IGBT switches are controlled by using one of the output ports of the development board (the D_0 and D_1 bits) and via the analog input channels AD_0 and AD_1 it is acquired the load current of the *H*-type bridge. With the same efficiency can be controlled other type converters as well, for example the power converter from figure 38.

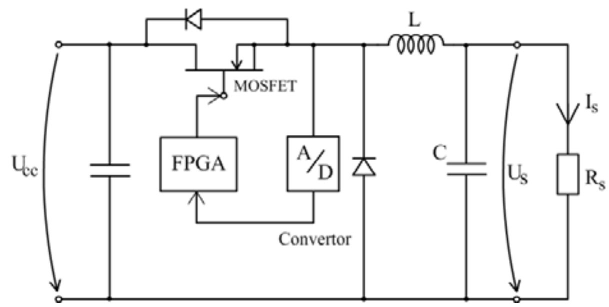

Fig. 38. FPGA-based control of a voltage converter

This block diagram presents a *Buch*-type voltage converter, where the power switch (the MOSFET transistor) it is controlled by using an FPGA processor. It means that in this concrete case the FPGA is uploaded with the program task which implements the U_s output voltage control.

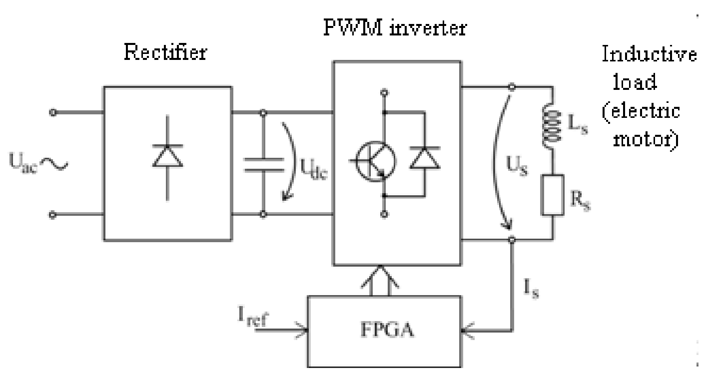

Fig. 39. FPGA-based PWM control of an inductive load

In figure 39 it is presented a frequently meet industrial application where the PWM control of a power electronic converter connected to an inductive load is required. In most of the cases this load is an electric motor phase winding. In such cases a FPGA processor can solve with success the real-time processing requirements and to execute with high speed the implemented control tasks or programs.

III. AREAS OF COMPETENCE COMPLEMENTARY TO ELECTRICAL ENGINEERING

3.1. FAULT-TOLERANT ELECTRICAL DRIVES DECELOPMENT AND IMPLEMENTATION - A BIOLOGICALLY-INSPIRED APPROACH

With the highly increasing trend of the computational and processing power of the new generation programmable VLSI (Very Large Scale Integrated) logic circuits, the fault tolerance problem involves huge problems for the designer engineers. The traditional fault detection methodologies become very inefficient and expensive. The alternative for those all problems was inspired from the living biological organisms, which are proved with remarkable surviving and fault-tolerance properties. Through a miraculous and well organized cooperation of a huge number of elements called the cells, the biological organisms involve a nearly perfect self-organization, self-reproduction (multiplying) and fault tolerance (cicatrisation) properties in a well organized hierarchical mechanism. The researchers from informatics and microelectronic sciences have early discovered the high possibilities through implementing of those miraculous properties on modern VLSI digital systems [25]. Those all research efforts are based on a new concept born on the digital systems design: embryonic systems. In this reason basic concepts from cellular embryonic theory could be used for VLSI digital systems design. Therefore terms like artificial molecule, artificial cell and artificial organism are key concepts in development and implementation of bio-inspired hardware systems.

Similarly with an embryonic organism evolved from a fertilized cell, the embryonic systems imports properties of the cellular organization, and implements on digital systems which shows complex evolution, fault-tolerance, and self-reproduction behaviors. From theoretical point of view, concepts from cellular embryology are used for VLSI digital systems design and development. The embryonic science in fact applies the basic characteristics of the living biological cells: multi-cellular organization (the artificial organism is build with a finite number of artificial cells); cells differentiation (each cell inside of an organism is characterized through a special function, and this process is depends essentially from the internal position of the cell in the organism); cells division (in artificial life the mother-cell has a DNA copy defined through initial parameters, which in the division process is transmitted to neighbor cells, until all cells from the network are programmed with the same properties) [26].

In analogy with the evolutionary processes of the biological systems, researcher E. Sanchez (EPFL Lausanne) introduced the POE (Phylogeny, Ontogeny and Epigenesis [27, 28]) classification for the digital electronic systems evolution, which model is indicated in figure 40. This model shows the dynamics of the international scientific researches in the thematic area in which is included the proposed project.

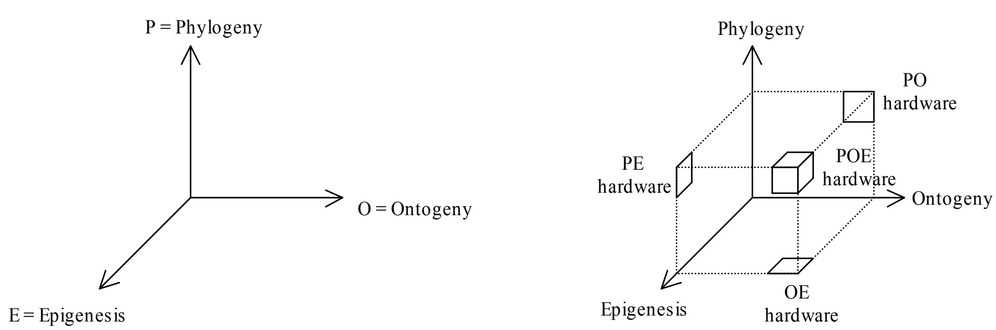

Fig. 40. The POE model for the hardware systems evolution [27]

The phylogeny principally is involved with the genetic evolution of the biological species. In engineering this correspond to genetic algorithms and evolution digital systems. Epigenesis is chained with the learning and adaptation processes (example: human nerve system, immunity system, endocrinology system, etc.) The ontogeny is the evolution of the organism from one cell to an adult organism, and involves the multi-cellular organization, cells differentiation and cells division, respectively the individual development and evolution controlled through the genetic code. Each physical cell will copy the original genome from the mother-cell. As a result, four combinations are made for the POE model:

- *PO hardware* – re-generable hardware systems, with evolution capabilities;
- *PE hardware* – hardware systems with learning capabilities, with evolution and adaptation behaviors;
- *OE hardware* – hardware systems with learning and self-reproduction (multiplying) capabilities;
- *POE hardware* – digital systems with learning, evolution and self-reproduction behaviors in multi-cellular structures.

In fact, this model is the basic structure of the embryonic systems, which's fundamental principle consists on cell-based hardware architectures (electronic artificial cell), with the purpose to build bigger organisms, similar with the embryonic evolution of the biological cells. Similarly with an embryonic organism evaluated from a fertilized cell, the embryonic systems imports proprieties of the cellular organization, and implements on digital systems which shows complex evolution, fault-tolerance, and self-reproduction behaviors. The embryonic science in fact applies the basic characteristics of the living biological cells:

- *multi-cellular organization* (the artificial organism is build with a finite number of artificial cells);
- *cells differentiation* (each cell inside of an organism is characterized through a special function, and this process is depends essentially from the internal position of the cell inside the organism);
- *cells division* (in artificial life the mother-cell has a DNA copy defined through initial parameters, which in the division process is transmitted to neighbor cells, until all cells from the network are programmed).

The international research efforts in bio-inspired hardware systems (embryonic science) are very intensive and dynamic. This large interest is caused through the huge problems in the more complex VLSI circuits manufacturing processes, which involves hardly problems for designer engineers (manufacturing errors, circuits size, fault tolerance, etc.), and through the large impact in the informatics an microelectronics technologies development (VLSI circuits minimization, atomic scale, and nanotechnology scale integrated circuits manufacturing). At the international stage two basic models has been developed for the bio-inspired digital embryonic systems:

- *the architecture with four levels embryonic structure* developed at the Swiss Federal Institute of Technology;
- *the architecture with two levels embryonic structure*, developed at University of York, England;

Taking into account the differences between the real world, -biological and digital systems, in the Logic Systems Laboratory from Swiss Federal Institute of Technology, EPFL Lausanne, it was developed a bio-inspired system architecture, founded in four level of organizing, as is shown in figure 41 [27, 28].

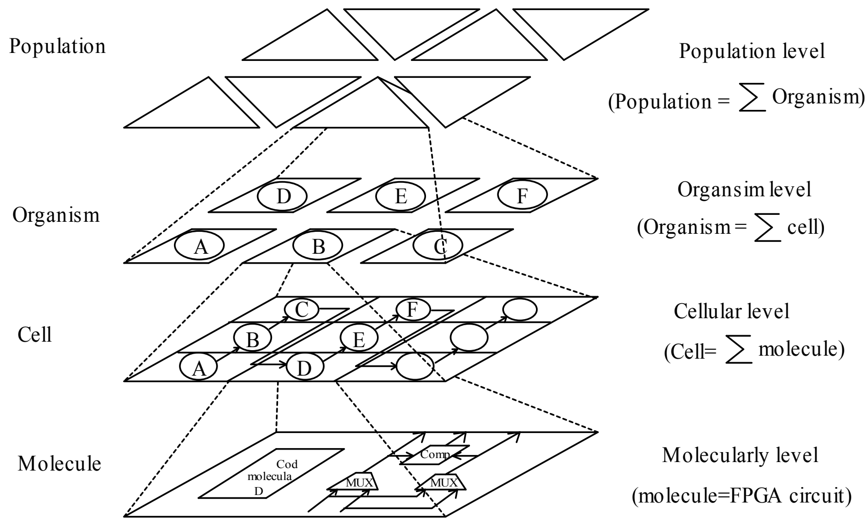

Fig. 41.The four levels of an embryonic system (Swiss Federal Institute of Technology)

According to this model, a population is composed from a finite number of organisms. In analogy with the living organisms from biological world, an artificial organism (embryonic machine) has a finite number of cells. Each cell is one processor (cellular automate) which realize a special function inside of the organism, defined through on set of instructions (program), which is named the cell's gene. The basic level of the bio-inspired digital systems is the molecularly level, implemented on bi-dimensional programmable logic elements, named as FPGA arrays. The FPGA circuit are ideal elements through special functions could be programmed, using the software configuration capabilities of those circuits. The special functions will represent the molecule code. Several PFGA circuits connected in network (virtually reproducing any kind of digital circuit architecture), will be able to reproduce an artificial cell architecture.

The architecture with two level embryonic structures, developed at University of York, England, is presented in figure 42 [29, 30, 31]. This model is based on a bi-dimensional matrix structure of cells. Each embryonic cell has a self-repairing mechanism of the gene, and an optimized memory space, together with a diagnose unit, I/O router, and a reconfiguration bloc, respectively a coordinate generator. The cells are capable for auto-localization inside of the cell array, can detect the internal faults of genes and have the capability of those self-repairing (cicatrisation).

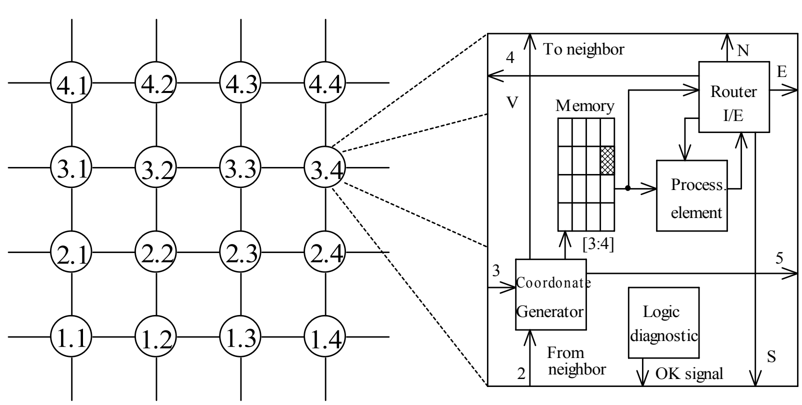

Fig. 42. The two levels of an embryonic structure (University of York, England)

Considering the above expressed theoretical remarks, in the Digital Control systems laboratory has been proposed an original developmental approach. A model which is suitable to cover in a single architectural configuration both the inter-cellular and intra-cellular phenomena's of a biological organism is proposed. The essence of this approach is expressed in figure 43, where a tissue-topology on two-layer coarse-fine-grid network model is introduced. Considering the incredible complexity of a three-dimensional extension, in this paper we are focusing solely on a two-dimensional (2D or tissue-topology) implementation strategy, abbreviated as 2D2L-CFG (coarse-fine-grid) model.

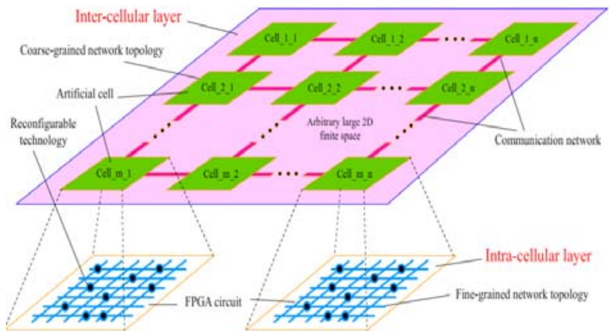

Fig. 43. The tissue-topology on two-layer coarse-fine-grid artificial organism model

The upper-layer of this model is made on a coarse grid topology of an arbitrary number of artificial cells (each represents the equivalent of a real biological cell) organized in a 2D matrix configuration. Within our approach, only the inter-cellular phenomena flow in this layer, such as: inter-cellular communication, cells self-replicating, growth, self-healing phenomena, faults accommodation, etc. These tasks all are managed by adequate network algorithms. The intra-cellular layer is developed upon a fine-grained reconfigurable network topology which is suitable for the embedding and reproduction of the biological cells internal metabolism.

For the purposes of validating the model by experimental development, a medium complexity *Spartan-3E Starter Kit* development board as shown in figure 44 ought to be sufficient. If the hardware platform built upon a 2D network of such boards works properly and fully validates the 2D2L-CGD modeling approach, the next step will be to improve the system performance and to upgrade it with Virtex-5, 6, 7 family development boards.

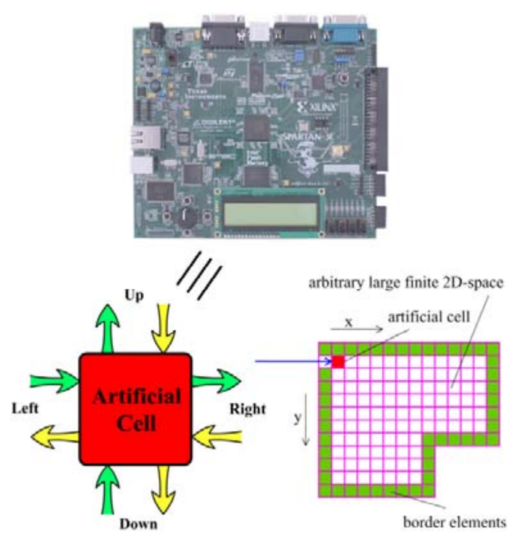

Fig. 44. Artificial cell developed upon FPGA-based main board frame

For the first laboratory tests, a platform composed of 9 artificial cells (one organism) was built up and tested as shown below in figure 45.

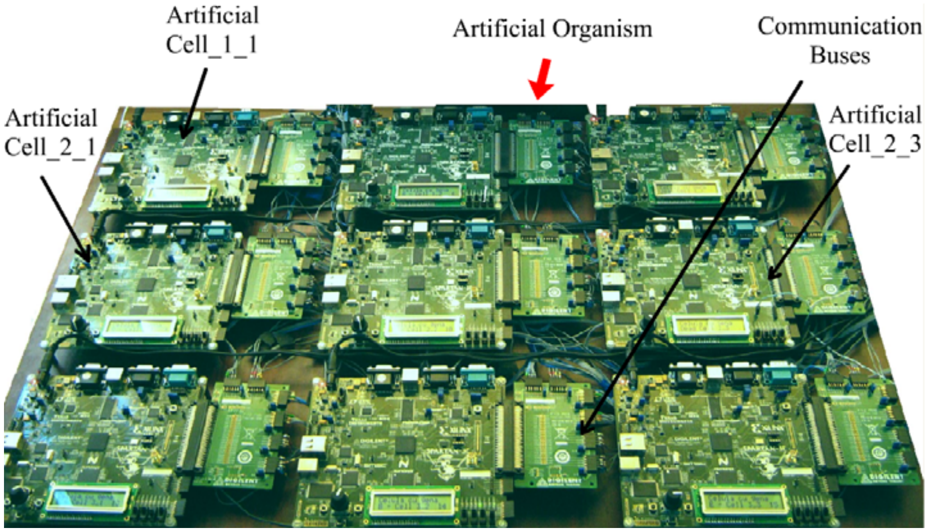

*Fig. 45***.** *Experimental setup: the artificial organism built upon the 2D2L-CFG model [32]*

There are 5 active cells, each expressing one active gene (A, B, C, D, or E), and 4 spare cells. The state of the cells and the configuring genome are displayed on the *LCD* ports available on each board. The wiring buses that connect the artificial cells together in a coherent group are closed along short pathways without any real chance of communication hazards or the occurrence of accidental electrical noise. Each artificial cell is also supplied by its own power supply circuit that increases the platform's general reliability coefficient. However, the most important behavior of the entire structure is that it covers a completely autonomous bio-inspired system. Once the first cell on either lattice of the organism is fertilized (in our case it means the VHDL-implemented algorithm uploaded through USB communication) the network has its own independent evolution and growth. All vital functions and self-repairing behaviors are managed inside the network without any external supervision, intervention, or external control unit. Of course, this doesn't mean that the cellular network designer can't keep track of any state or information flow inside the system by means of the generous display resources (*VGA* ports or *LCD* display), or even by the use of a high efficiency oscilloscope connected to the desired points of the system.

3.2. ELECTRICAL DRIVES DIGITAL CONTROL SYSTEMS PROGRAMMING

Electrical drives digital control systems development and implementation also requires high level programming skills and knowledge of last generation software toolkits. In the Digital Control Systems laboratory the available hardware systems are programmed by using software toolkits such as the Twido-Suite ladder logic, Intel Pentium assembly language, VHDL description language, the graphical oriented LabView, micropascal, etc. In order to outline the competences and programming skills gained in the last around fifteen years, in the followings will be presented same short examples of digital control systems programming.

As it is well known, PLCs usually are programmed by using the ladder logic diagram. In figures 46 and 47 are presented an example of programming in the Twido-Suite software toolkit the PWM control strategy of a DC motor, respectively how can be settled the PWM modulation parameters by using the ladder logic diagram.

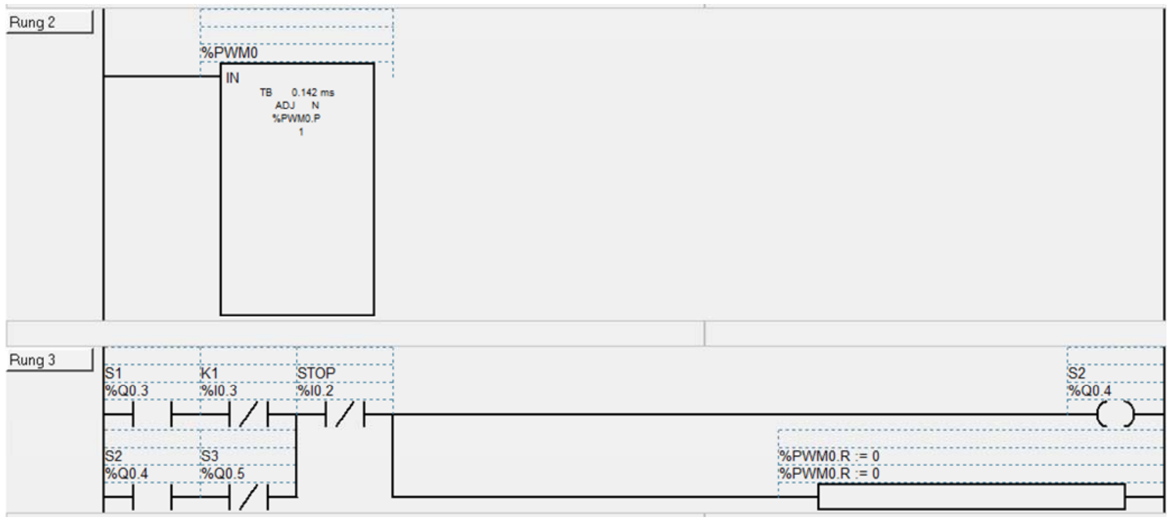

Fig. 46. The PWM modulation of a dc motor supply voltage [33]

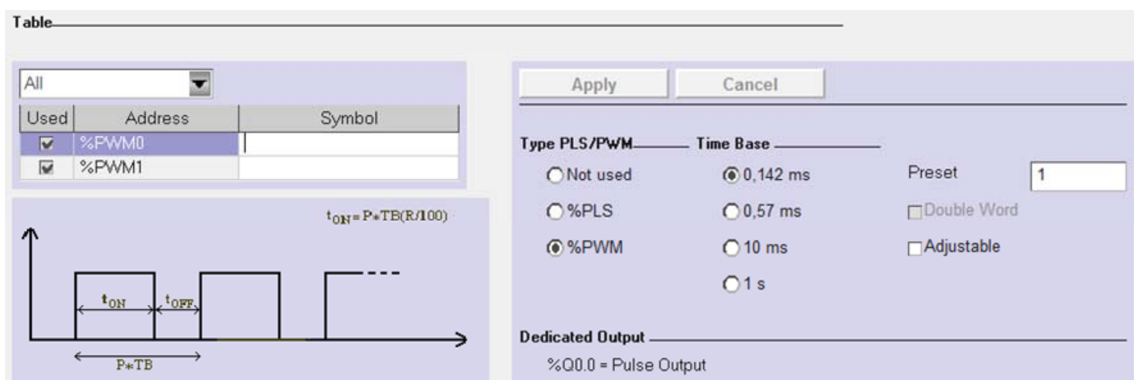

Fig. 47. Setting the PWM modulation parameters [33]

FPGAs are programmed in the VHDL description language or Verilog. In the laboratory it is available the Xilins ISE software toolkit allowing VHDL projects development. For example, to test the *Digilent BasysBoard* development module can be considered the simply case when a 3 bit counter circuit is implemented in the VHDL language. There will be defined the following signals for the FPGA chip:

- Input signals: *clk, up, down, Sw_0, Sw_1, Sw_2, Sw_3, Osc* and *reset*;
- Output signals: *Digit_0, Digit_1, Digit_2, Digit_3*;
- Buses: *Q* input on 4 bits (3-0) and *Display* as output on 7 bits (6-0).

In the program architecture declaration will be inserted the following VHDL source code:

```
entity Numarator_3b is
   Port ( clk : in  STD_LOGIC;
        up : in  STD_LOGIC;
        down : in  STD_LOGIC;
        Q : out  STD_LOGIC_VECTOR (2 downto 0);
        Digit0 : out  STD_LOGIC;
        Digit1 : out  STD_LOGIC;
        Digit2 : out  STD_LOGIC;
        Digit3 : out  STD_LOGIC;
        Sw3 : in  STD_LOGIC;
        Sw2 : in  STD_LOGIC;
```

```
          Sw1 : in  STD_LOGIC;
          Sw0 : in  STD_LOGIC;
          Osc : in  STD_LOGIC;
          reset : in  STD_LOGIC;
          Display : out  STD_LOGIC_VECTOR (6 downto 0));
end Numarator_3b;
architecture Behavioral of Numarator_3b is
  signal count : STD_LOGIC_VECTOR (2 downto 0):= "000";
  signal count_direction : STD_LOGIC := '1';
  signal MainCounter: STD_LOGIC_VECTOR (19 downto 0):= "00000000000000000000";
  signal DebQ1, DebQ2, DebQ3 : std_logic;
  signal DebClk: std_logic;
begin
  Digit0<=Sw0;
  Digit1<=Sw1;
  Digit2<=Sw2;
  Digit3<=Sw3;
  Q<=count;
  process (up, down)
-- bistabil Set/Reset
    begin
             if up='1' and down='0' then
               count_direction<='1';
             end if;
    if up='0' and down='1' then
               count_direction<='0';
             end if;
  end process;
--  process (DebClk, Reset)
--  begin
--    if Reset = '1' then
--      count <= "0000";
--    else
--      if DebClk = '1' and DebClk'event then
--        if count_direction='1' then
--          count <= count + 1;
--        else
--          count <= count - 1;
--        end if;
--      end if;
--    end if;
--  end process;
  process (DebClk, Reset)
  begin
    if Reset = '1' then
      count <= "000";
    else
      if DebClk = '1' and DebClk'event then
        if count_direction='1' then
          if count = "111" then
            count <= "001";
          else
            count <= count + 1;
          end if;
        else
          count <= count - 1;
        end if;
      end if;
    end if;
  end process;

  with Count Select
     Display<= "1111001" when "001",   --1
         "0100100" when "010",   --2
         "0110000" when "011",   --3
         "0011001" when "100",   --4
         "0010010" when "101",   --5
         "0000010" when "110",   --6
         "1111000" when "111",   --7
         "1000000" when others;   --0
-- eliminarea vibratiilor mecanice ale butonului
  process (Osc)
  begin
    if Osc = '1' and Osc'event then
      MainCounter <= MainCounter + 1;  -- divizor de frecventa
    end if;
```

```
 end process;
  process(MainCounter(17))
 begin
  if (MainCounter(17)'event and MainCounter(17) = '1') then
    DebQ1 <= clk; --buton
    DebQ2 <= DebQ1;
    DebQ3 <= DebQ2;
  end if;
 end process;
 DebClk <= DebQ1 and DebQ2 and (not DebQ3);
end Behavioral;
```

By successively pressing the *clk* button pulses will be generated on the counter input, which will be countered on 3 bits. The result it is displayed then on the 7-segment decoder circuit. The signals *up* and *down* sets the count direction and the *reset* signal it is used to initialize the counter.

For graphical oriented programming purposes the national Instrument's LabView software package looks a very powerful and useful toolkit. The next example from figure 48 outline the versatility of this software built up upon the graphical Virtual Instruments (VIs) concept. There is an intelligent building supervising and event monitor system developed in the LabView where the input information is considered the building's cadastral plan in a *.jpeg* or *.bmp* file format. Here an arbitrary chosen building plan is indicated, free downloaded from the *www.schwabinvest.hu* internet page. The program supervises all the doors and windows status (open or closed), the lighting system of the building, and the state of the heating elements (turn off/turn on).

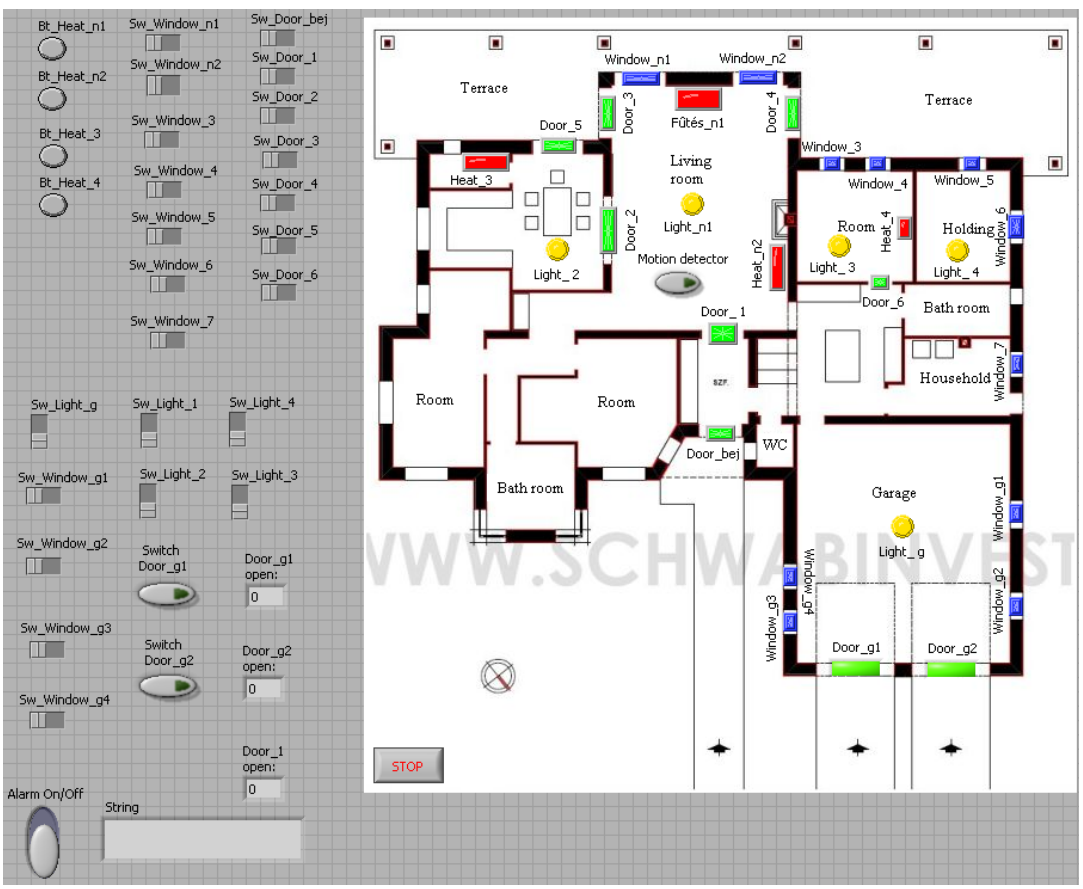

Fig. 48. The front panel of the implemented LabView program

In the front panel of the LabView software-based development system the state of the doors, windows, lighting elements, fan coils or heating elements are indicate by two-state (logical 0/1) switches, as is presented in figure. 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 the windows of the building are closed, otherwise 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.

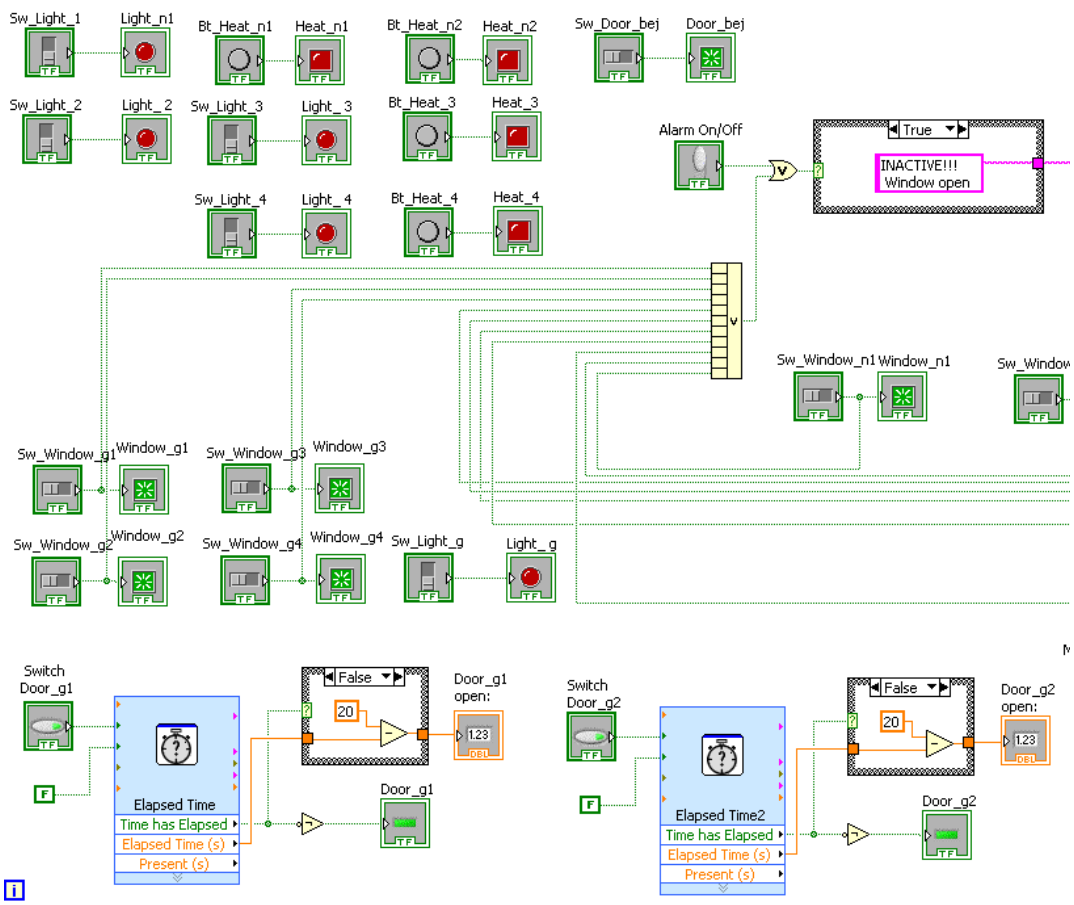

Fig. 49. The block diagram of the implemented LabView program

A part of the block diagram resulting from the implemented building supervising and monitor system is shown in figure 4. The developed program is well suitable for a wide range of settings, modifications, of configurations, in accordance with customer needs and wishes. The only one limitation is linked with the complexity of the given building plan. In case of a very complex buildings (high-rise buildings, a big number of rooms, etc.) the cadastral plane and all the sensors and switches must to fit into the LabView environment's design desktop.

IV. MEMOIR OF TECHNICAL-SCIENTIFIC ACTIVITY AND RESEARCH RESULTS

As it has been mentioned before, this habilitation thesis is a summary of the research performed over a period of around fifteen years, covering the time interval since the defense of the PhD thesis in April 1999 and until this habilitation was printed in 2014. During the above mentioned time period the scientific activity and research results has been synthesized in a total number of 101 publications as follows:

- 10 books
- 1 national patent;
- 4 ISI papers;
- 67 international conference papers (21 indexed in international databases)
- 19 publications in international or national journals.

The scientific and research activity of this time interval is also completed by 5 national and international research projects (as member or project director).

4.1. ELECTRICAL DRIVE SYSTEMS CONTROL STRATEGIES DEVELOPMENT AND IMPLEMENTATION

The first years of the research activity was focused on the electrical drives digital control systems development and implementation, with a special attention on servomotors-based systems modeling, simulation, and experimentation. Dynamic performances evaluation of the vector-controlled permanent magnet hybrid stepping motor are presented in the papers [34, 35], respectively the simulation and modeling of the same control strategy in [36, 39]. In references [37, 43, 47, 51] it has been detailed analyzed the effects of a H_2 robust control strategy implementation for servo drive systems. Papers [38, 40] describe a low-power current-source PWM inverter design methodology and experimentation for two-phase bipolar stepping motors widely used in servo drive automation systems. There are presented detailed electronic circuits, simulation results, respectively laboratory measurements of a versatile the power electronic module specially conceived for stepping and d.c. motors closed-loop drive. Several papers published in IEEE Xplore indexed international conferences deals with modern control strategies implementation for servomotors-based control systems. Among these are remarked the references [41, 42, 46] presenting sliding-mode robust control strategies for electrical drive systems, with careful simulation and laboratory experimental results as well. A high performance fuzzy controller-based control system for low-power motors is described in the papers [44, 55]. At the same time variable structure controllers implementation for closed-loop servomotor-based systems are detailed presented and explained in the works [49, 50, 54]. Beside the above mentioned modern control strategies the classical PID position and velocity controller implementation for servomotors also has been experimented in the Digital Control Systems laboratory [49].

Furthermore, during the postdoctoral research stage at TUAT University in Tokyo a special attention was focused on the linear synchronous motors design, development and implementation. There have been studied special type linear synchronous motors with application in health service tray systems, designed and experimented for elderly persons. The paper [45] describes such kind of health service tray system. This is a specially developed 3-phase actuator for health service tray systems applications with a mover incorporating a permanent magnet into its electromechanical structure, as shown in figure 50. The motor it is driven by a PWM power electric converter composed of three identical modular units (fig. 51). Each module is in fact a current source inverter units supplying one phase of the linear actuator, built up by using an integrated L6203 SGS Thomson bridge of bipolar transistors.

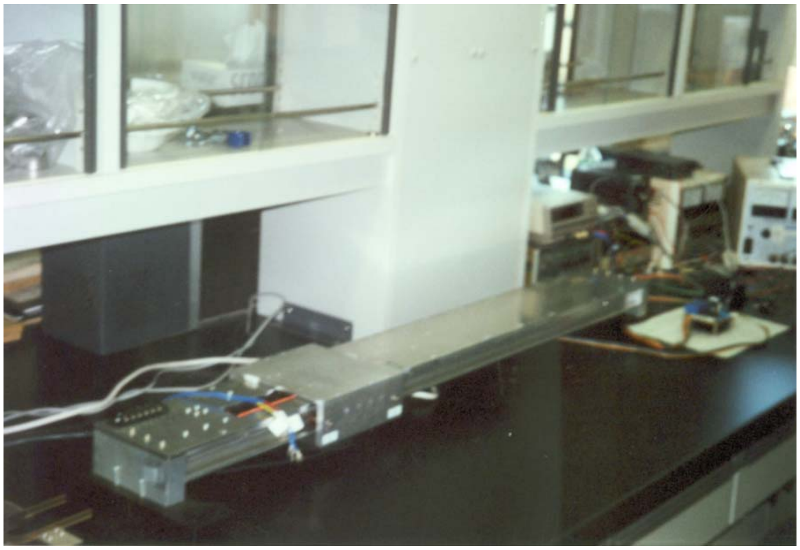

Fig. 50. Linear synchronous motor for health service tray systems development (Department of Environmental and Symbiotic Production Systems, Graduate School of Bio-applications and Systems Engineering, TUAT, Japan)

The maximal voltage supply of the inverter is 46V, for a maximal 4A phase load current. The current source inverter module it has been so conceived that any kind of reference signal generated by the digital control unit to the converter inputs can be reproduced with high fidelity in the motor phases. This property allows a great freedom for the digital control designer, because any kind of closed-loop control strategies of the linear motor can be implemented and tested without any changes in the power converter side.

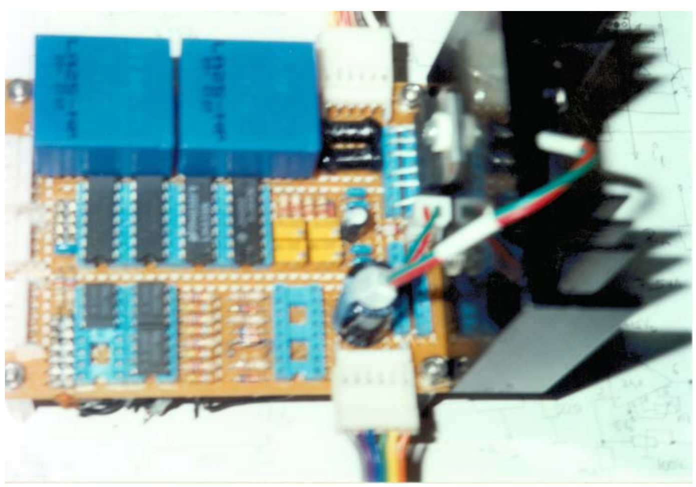

Fig. 51. PWM inverter unit for the linear synchronous motor drive (Department of Environmental and Symbiotic Production Systems, Graduate School of Bio-applications and Systems Engineering, TUAT, Japan)

In the same way, reference [52] presents the applications of linear synchronous motors in railway systems. The given actuator is a modularized linear synchronous motor, driven by a PWM converter, and provided with an incremental position encoder mounted across the length of the mover motion of. Pictures indicating the electromechanical structure of the linear synchronous motor with its main parts and components are shown in figure 52.

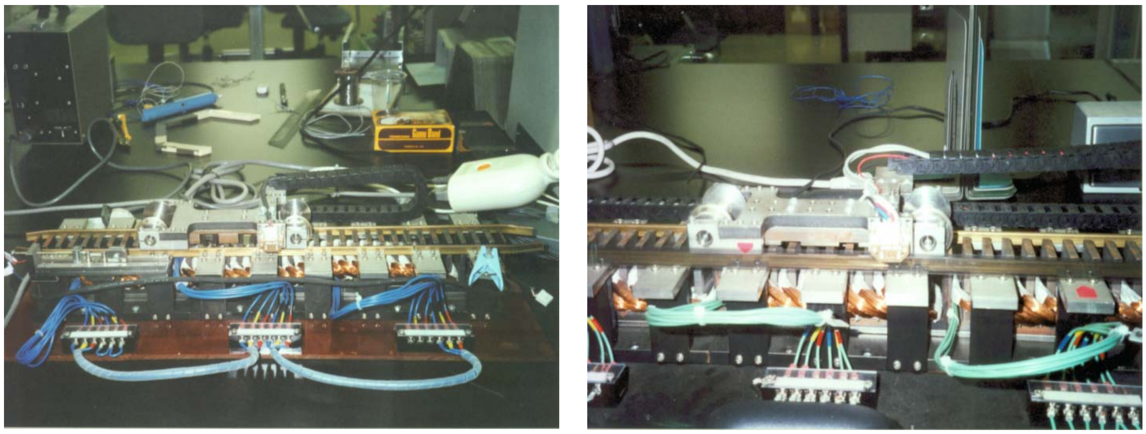

Fig. 52. The linear synchronous motor structure (Department of Environmental and Symbiotic Production Systems, Graduate School of Bio-applications and Systems Engineering, TUAT, Japan)

A special type of current-source PWM inverter for servomotors drive it has been introduced in the paper [56]. This research work proposes a next generation single-chip smart inverters development strategy for low-power motors drive in high performance embedded automation systems. The main idea of this paper is that it is possible to develop a new generation of power electronic smart ICs being fully compatible with a large scale of digital control systems without any interfacing circuit.

4.2. ELECTRICAL DRIVES DIGITAL CONTROL SYSTEMS DEVELOPMENT AND IMPLEMENTATION

4.2.1. Hardware-in-the-loop control system development and implementation.

As it is well known, the hardware-in-the-loop (HIL) technique combines the mathematical simulation model of a system (or plant) with actual physical hardware, by capturing closed-loop bidirectional interactions between its physical and virtual constituents, being one of the most widely used synthesis paradigm in real-time embedded systems prototyping [57, 58]. In other words, it is a synthesis paradigm combining many advantages of both of physical and virtual prototyping of complex real-time embedded control systems. The major advantage of this method is considered its cost effectiveness, in the vast majority of applications requiring significantly less hardware then fully physical prototypes. At the same time, the HIL implementation remarks in many applications with higher processing speed by enabling concurrent systems engineering as well and outstands through its non-destructive nature, often making possible to simulate a wide range of destructive or irreversible events, avoiding costly experiments and tests [59, 60, 61]. Not at least it s important to remark the HIL strategy offer a high degree of repeatability and comprehensiveness, often making possible experiments in a wide range of operating conditions than what is feasible via physical prototyping. However, it is no doubt that modern engineering systems require a high degree of prototyping and HIL simulations and implementations has become indispensable in many demanding industrial applications [62].

In the Digital Control Systems laboratory has been experimented a microcontroller-based HIL system development strategy for real-time control algorithms prototyping purposes [62]. There an original implementation solution unfolded upon a microcontroller-based hardware-in-the-loop configuration, designed and developed with the basic scope to prototype real-time control algorithms for high performance industrial applications. The hardware module of the system is a BigPIC6 development board which has been interfaced with a plant modelled in the Matlab/Simulink software environment, as shown in the block diagram from figure 53 [63]. The result is a powerful and versatile system well suitable for control algorithms design and development.

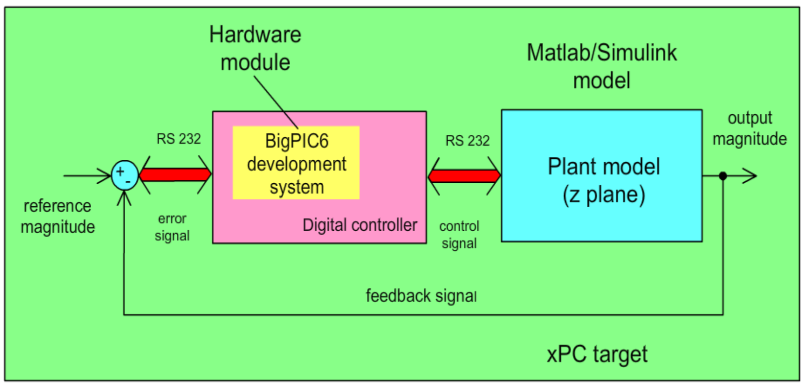

Fig. 53. The block diagram of the microcontroller-based HIL simulation system [62]

The HIL system development effort lies on the classical closed-loop control theory main concepts. According to this, the control loop of a closed system will be broken, by acquiring the error signal via a microcontroller-based hardware development system. Then the captured signal will be real-time processed, according to the algorithms and rules implemented on the digital controller unit. As shown in figure 53, the loop it is closed by connecting the digital controller output to the plant input and providing the novel control signal. The Matlab/Simulink model of the controlled process is connected to an actual physical hardware, by capturing closed-loop bidirectional interactions (RS 232 communication) between physical and virtual constituents.

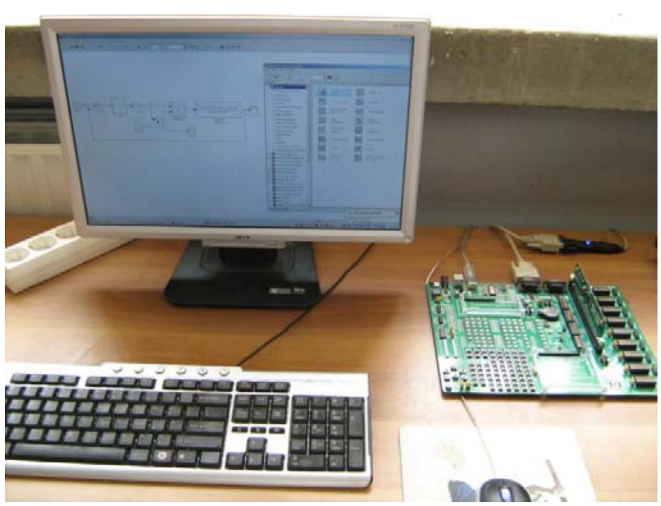

Fig. 54. Laboratory setup: the HIL development system

Therefore, the BigPIC6 development system-based digital controller, embedding a Microchip PIC-type central processing unit it is integrated with a software model and will perform realistic operating conditions, by processing real-time control algorithms. It is self-understanding that in such a digital control system the plant model is expressed in the *z* plane, and the numerical simulation is running on *xPC* target. In figure 54 it is presented the entire HIL simulation development system where the digital controller has been integrated into the Matlab/Simulink simulation environment. There BigPIC6 development board interfaced via its RS-232A serial port to the personal computer's serial communication. On the *xPC* target's monitor can be followed the running Simulink model which passes the computed floating-point signed values via its serial port to the digital controller. This hardware unit decodes the captured information, processes it according to the implemented algorithm, and then returns the result to the personal computer. The information will be a floating-point signed value introduced as an input control signal to the plant given in the Matlab/Simulink model. Experimental results prove the efficiency of the developed HIL simulation system, providing a useful tool both for modeling and experimental purposes.

4.2.1.1. Real-time PID control algorithms prototyping in a microcontroller-based HIL system

Once the laboratory setup HIL simulation system has been experimented and tested in the next research step careful HIL simulation efforts were started by prototyping real-time PID controller implementation algorithms. These HIL simulation efforts follow a simple idea. It is considered an arbitrary chosen plant with its function transfer expressed in the *z* plane as follows:

$$H_p(z) = \frac{0.001586 \cdot z^2 + 0.006035 \cdot z + 0.001435}{z^2 - 1.81 \cdot z + 0.8187}. \tag{1}$$

Then the given plant it is included into a Matlab/Simulink model-based closed-loop control system as shown in the block diagram from figure 55.

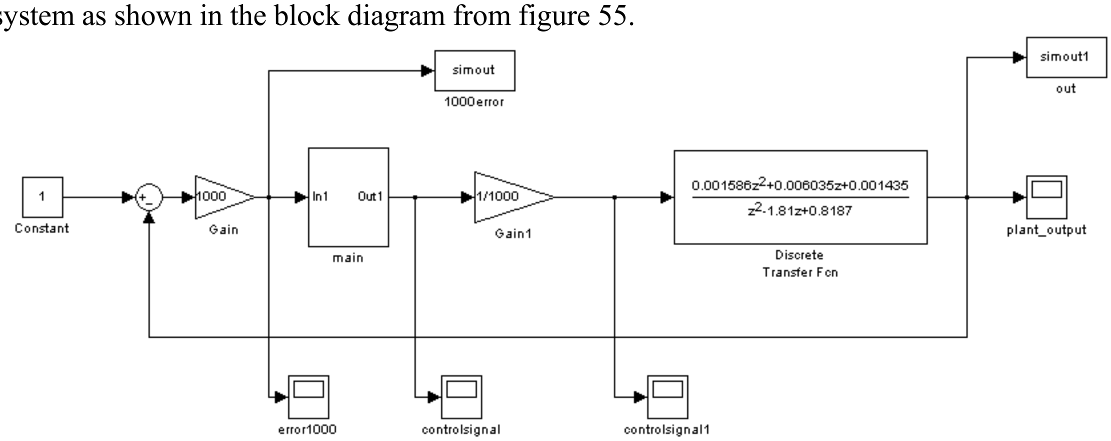

Fig. 55. The Simulink model of the hardware-in-the-loop simulation system

There the *main* Simulink block with its *In1* and *Out1* input/output signals represents the communication interface between the mathematical model and the BigPIC6 development system-based digital controller. Then in the Simulink model for a given set of the simulation parameters the dynamic response of the system is measured and evaluated. For the same parameters and conditions a HIL simulation of the system is performed by using the experimental setup presented in figure 54. If the obtained results for the two different simulation strategies are near the same, then it can be considered that the experimental results covers the theoretical ones, and the HILS system works properly. For example, if proportional coefficient is $k_P=2.9$, the integration coefficient is chosen $k_I=0.001$, and the derivative coefficient to $k_D=1$, the results plotted in figure 56 and figure 57 will be obtained.

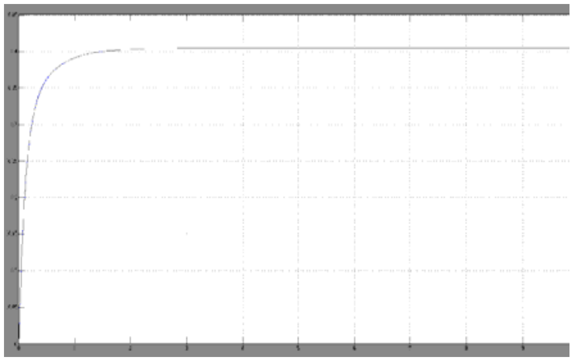

Fig. 56. The system response in Matlab/Simulink simulation (z plane, $i_R=0.45$, $k_P=2.9$, $k_I=0.001$, $k_D=1$, $T_s=0.01s$)

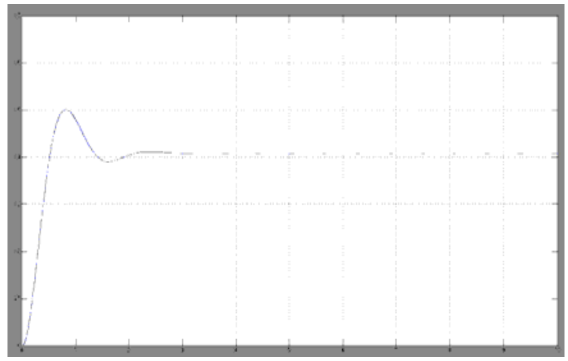

Fig. 57. The system response in HILS ($i_R=0.45$, $k_P=2.9$, $k_I=0.001$, $k_D=1$, $T_s=0.01s$)

By tuning more appropriate simulation parameters the above presented results can be improved significantly. There is the situation of the figures set figure 58 and figure 59, where the $k_P=3.1$, $k_I=0.0045$, and $k_D=1$ simulation parameters has been settled.

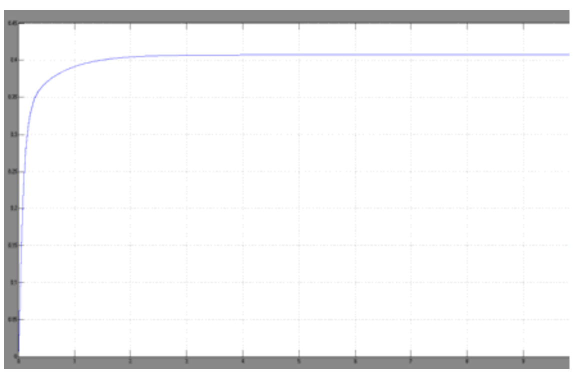

Fig. 58. The system response in Matlab/Simulink simulation (z plane, $i_R=0.45$, $k_P=3.1$, $k_I=0.0045$, $k_D=1$, $T_s=0.01s$).

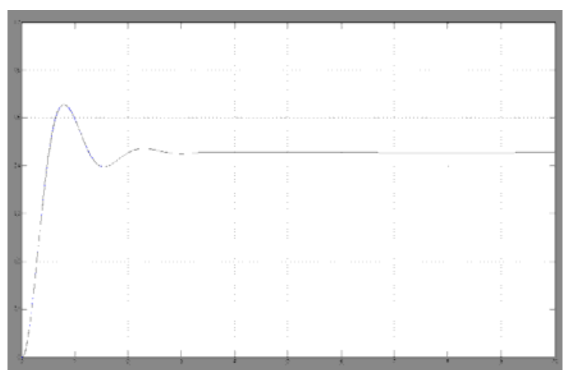

Fig. 59. The system response in HILS ($i_R=0.45$, $k_P=3.1$, $k_I=0.0045$, $k_D=1$, $T_s=0.01s$).

This simulation set outlines that by choosing more appropriate *PID* controller parameters the steady-state error can be significantly diminished.

4.2.1.2. Real-time fractional control algorithms prototyping in a microcontroller-based HIL system

In agreement with Riemann–Liouville's conception, the notion of fractional order integral of order $\mathfrak{R}(\alpha) > 0$ is a natural consequence of Cauchy's formula for repeated integrals, expressed as [64]:

$$D_c^{-n} f(t) = \frac{1}{(n-1)!} \int_c^t (t-\tau)^{n-1} f(\tau) d\tau \,, \;\; t > c, n \in Z^+ \tag{2}$$

Introducing the Euler's *Gamma* function which is a generalization of a factorial:

$$\Gamma(n) = \int_0^\infty t^{n-1} e^{-t} dt \tag{3}$$

and extending (2) to $n \in R^+$, the fractional order integral became [64]:

$$D_c^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_c^t (t-\tau)^{\alpha-1} f(\tau) d\tau \,, \;\; t > c, \alpha \in R^+ \tag{4}$$

Dealing with dynamic systems, where it is usual that $f(t)$ be a causal function of t, the definition for the fractional-order integral to be used is:

$$D^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t-\tau)^{\alpha-1} f(\tau) d\tau \,, \;\; t > 0, \alpha \in R^+ \tag{5}$$

The definition (5) cannot be used for the fractional-order derivative by direct substitution of α by $-\alpha$, because it has to proceed carefully in order to guarantee the convergence of the integrals involved in the definition, and to preserve the properties of the ordinary derivative of integer-order. The Riemann–Liouville definition for the fractional-order derivative of order α □ R+ has the following form [18]:

$${}_R D^\alpha f(t) = \frac{d^m}{dt^m} \left[\frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f(\tau)}{(t-\tau)^{\alpha-m+1}} d\tau \right], \;\; m-1 < \alpha < m \,, \;\; m \in N \tag{6}$$

An alternative definition for the fractional-order derivative was introduced by Caputo as [64]:

$${}_C D^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{\alpha-m+1}} d\tau \,, \;\; m-1 < \alpha < m \,, \;\; m \in N \tag{7}$$

Due to its importance in applications, it must be also enumerated the Grünwald–Letnikov's definition of the fractional-order derivative, based on the generalization of the backward difference [65]:

$$\begin{aligned} {}_{GL} D^\alpha f(t) = \sum_{k=0}^{m} \frac{f^{(k)}(0^+) t^{k-\alpha}}{\Gamma(m+1-\alpha)} + \\ + \frac{1}{\Gamma(m+1-\alpha)} \int_0^t (t-\tau)^{m-\alpha} f^{(m+1)}(\tau) d\tau \end{aligned} \;\;, \;\; m > \alpha - 1 \tag{8}$$

As it is well known, in international references the most common form of a fractional order PID controller is given as a $PI^\lambda D^\mu$ controller, involving an integrator of order λ, and a differentiator of order μ where λ and μ can be any real numbers. The transfer function of such a controller has the following form [64]:

$$C_F(s) = K_P \left(1 + \frac{K_i}{s^\lambda} + K_d s^\mu \right), \;\; \lambda, \mu \in \Re \,. \tag{9}$$

The main advantage lies in the fact that the $PI^{\lambda}D^{\mu}$ controllers are less sensitive to changes of parameters of a controlled system [65]. This is due to the two extra degrees of freedom to better adjust the dynamical properties of a fractional order control system. Fractional-order systems are also used in studying the anomalous behavior of dynamical systems in chemistry, biology, viscoelasticity, chaotic systems, etc. It results that fractional calculus is useful both in the description and modeling of systems, and in a range of control design and practical applications [66, 67, 68].

4.2.2. PLC-based electrical drive systems development and implementation.

As it is well known the PLCs microprocessor-based digital systems used mainly in electromechanical processes automation, with the major scope to perform switching, timing, or monitoring operations in industrial processes control. In the Digital Control Systems laboratory it has been designed and implemented an industrial crane's model driven by a PLC-based digital control system, detailed presented in the paper [69]. The electromechanical part of this system consists of a metallic-frame which provides the adequate mechanical stability for the object three-dimensional manipulation. The movement in the *x* and *y* directions is facilitated by the 12V supply electric motors *M1* and *M2*. If the touch switches *K1* and *K2* are activated the mover reaches the movement limits along the axis *x*. The motor *M2* is responsible for the crane movement along the axis *y*, and the switches *K3* and *K4* indicates the limits of this freedom (fig. 60).

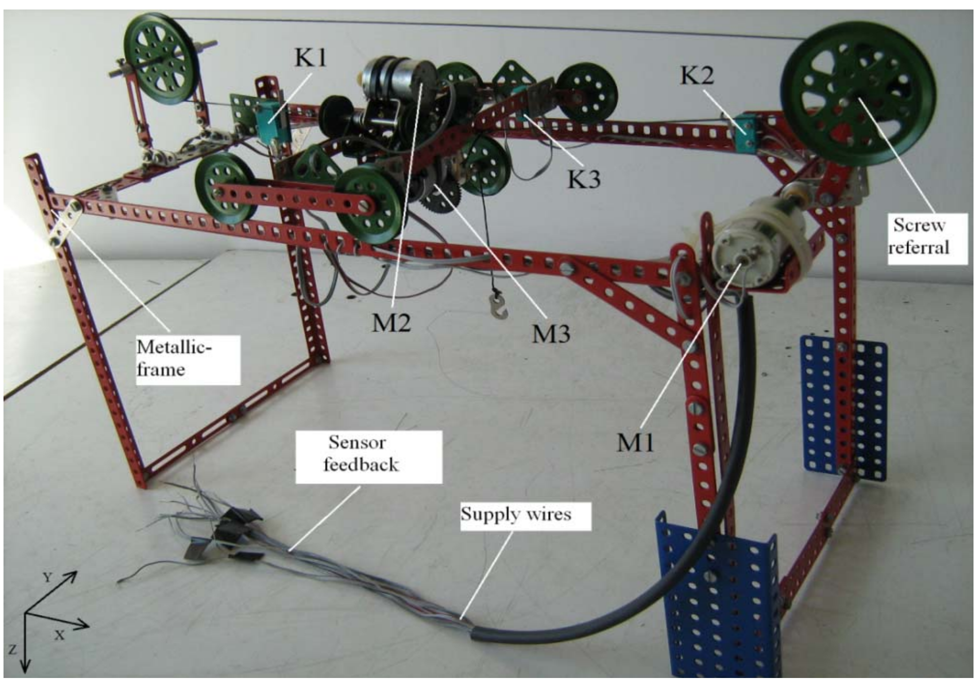

Fig. 60. The cranes electromechanical system [69]

The crane's movement along the *z* axis is provided by using the motor *M3*. Figure 61 shows the interconnection of the electromechanical system with the PLC-based digital control unit. By using the Ladder Logic graphical programming language various crane driver programs has been designed and implemented. In figure 62 it is presented the *M1* motor drive program providing the movement along the axis x. in order to avoid the unwanted mechanical oscillations, the DC motor is gradually accelerated by increasing its supply voltage.

Fig. 61. The industrial crane model laboratory setup [69]

This goal can be achieved by pulse width modulation (PWM) of the applied voltage supply pulses. In the next figure (fig. 63, 64) it is given the temporization module for the PWM logic implementation.

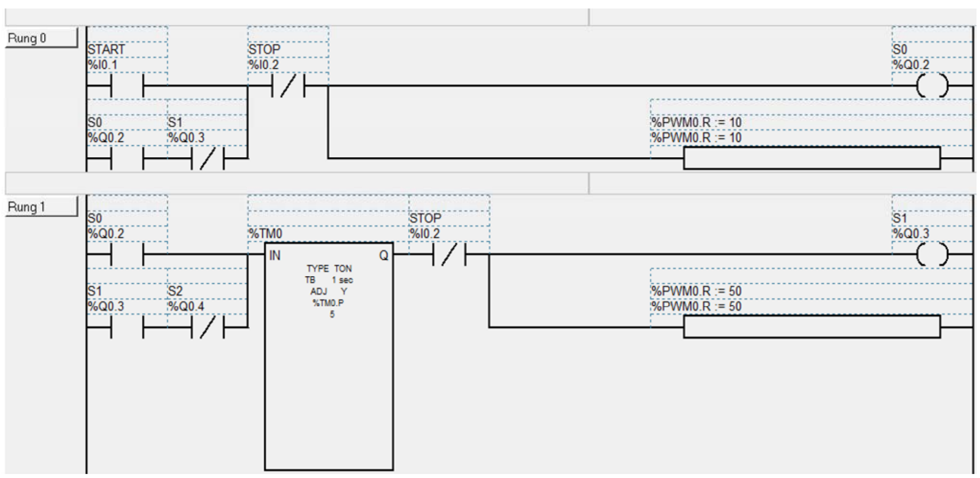

Fig. 62. The M1 motor drive program [69]

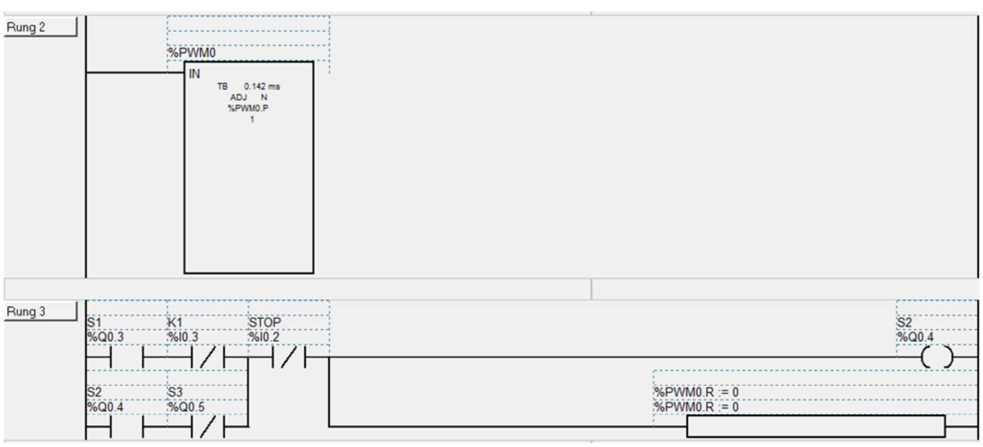

Fig. 63. The PWM modulation of the motor supply voltage [69]

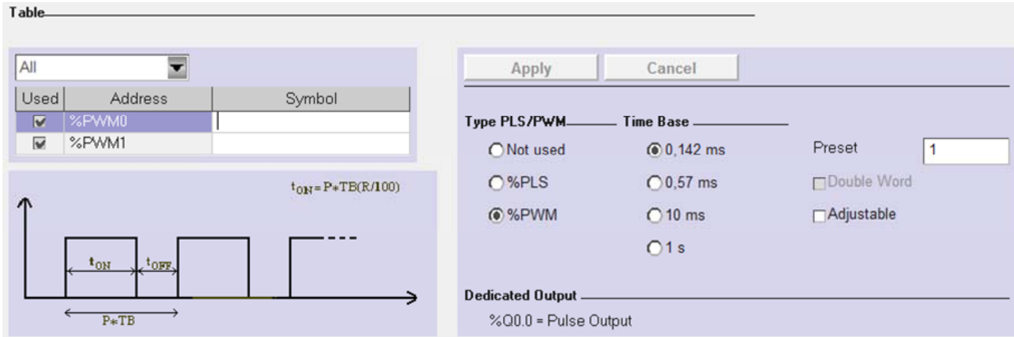

Fig. 64. Setting the PWM modulation parameters [69]

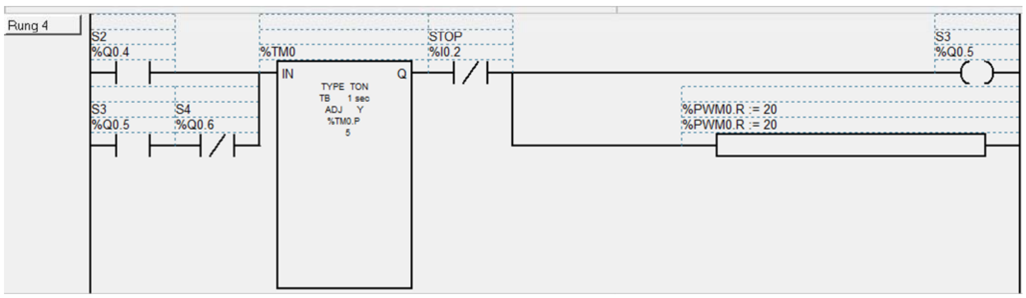

Fig. 65. The M3 motor drive program [69]

In this concrete case the PWM signal period has been settled for 0.142ms, the initial width of the supply voltage is considered 10% of this period. During the acceleration process of the motor this coefficient is gradually increased to the 50%. The M3 motor drive ladder Logic program is presented in figure 65.

4.3. FAULT-TOLERANT ELECTRICAL DRIVE SYSTEMS DEVELOPMENT AND IMPLEMENTATION

One of the most important research topics in the Digital Control Systems laboratory is the design and experimentation of fault-tolerant electrical drive systems for critical industrial applications. There the main efforts are focused on fault-tolerant power converters and fault-tolerant digital control systems development and implementation. The research results presented in this paragraph has been financially supported by two projects won by the author in national grants competition:

[1] *Theoretical and experimental research regarding the fault tolerance and self-organization properties implementation on digital and analogical bio-inspired systems***.** Research project CNCSIS, type A, CNCSIS code: 1571, Project manager: Dr. Szász Csaba, 2007-2008.
[2] *Fault-tolerant equipment controlled by bio-inspired electronic architectures.* Research project CNMPI2-Partnerships 2008, No: 12121/2008, Project manager: Dr. Szász Csaba, 2008-2011.

The obtained theoretical and experimental results having as subject the bio-inspired hardware systems design and development for fault tolerant electrical drive systems implementation have been presented in the volumes [5, 32]. Additionally, these research results also has been published in a high number of scientific papers published in IEEE Xplore indexed international conferences and high ranked journals. The main idea of this topic is that researchers from microelectronic sciences have early discovered, that by adopting self-healing and surviving mechanisms of biological organisms from nature, it becomes possible to design complex novel digital systems provided with highly fault-tolerance and robustness properties. The goal is to imitate the biological organism's cell-based structure which involves nearly perfect self-organization, and fault-tolerance abilities in a well organized hierarchical mechanism. Focusing on this strategy, it is expected to implement VLSI hardware structures able to reproduce biological cells or artificial organism basic functions in similar mode with their equivalents from the living world [70, 71]. As it is known, the immune systems found in higher evolutional level biological organisms is a distributed and multilayered system that is robust and able to identify infectious pathogens, injury, diseases, or other harmful effects. Therefore, their properties and abilities, like self-healing or surviving, would be more advantageous in many applications, where often are imposed robustness and also high security operation requirements. Taking inspiration from biological organism's immune system and embryonic processes it is possible to acquire these fault tolerant properties in hardware circuits. For this reason, the artificial embryonic systems have been applied to many different application areas, such as: hardware fault tolerance, industrial process monitoring, fault tolerant software, pattern recognition, electrical drives control, neural networks implementation, optimization and industrial control processes [72, 73, 74].

The first steps of the fault-tolerant electrical drives digital control systems design and implementation have been focused on artificial cellular models development and experimentation, such as artificial cell model or artificial organism model. An original development strategy and implementation of a generalized model for an FPGA-based artificial cell in bio-inspired hardware systems are presented in references [75, 76, 77]. Such an embryonic model is presented in figure 66.

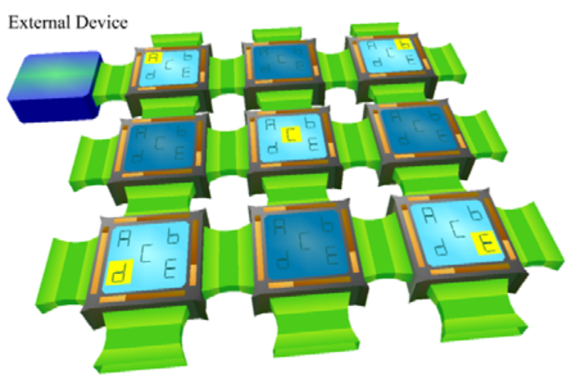

Fig. 66. Embryonic network cluster [93]

In this network, each artificial cell is considered a standalone powerful FPGA circuit, with abilities of full communication with neighbor cells (left, right, up, and down). The homogenous array of artificial cells will gain the properties of an embryonic structure only after each cell reach to known its own bi-dimensional coordinates in the network and express the gene which shows the cell's unique function. The set of all implemented genes, upon the artificial organism, is called here the *genome* or *artificial DNA*. In the presented model, the operative genome is designed with 5 *genes* (*A, B, C, D*, and *E*), and at the same time just one gene is shown active (highlighted in the figure). The cells, which don't show any operative gene, are considered spare cells (4 cells from the total of 9 in a cluster indicated in the figure).

In the next development steps artificial life and network communication strategy in embryonic systems with FPGA-based hardware has been elaborated. Then the network was endowed with self-healing and fault-tolerance abilities by using spare cells in the bio-inspired hardware system [78, 79, 81, 82, 83, 84, 85]. At the same time careful modeling and real-time simulation of embryonic structures for high reliability electrical drives has been tested, as it is presented in references [80, 86, 87, 88, 92].

Figure 67 shows a general view of the laboratory prototype experimental system for high reliability servomotor control, built upon bio-inspired hardware with self-replacing behaviors. There are two main hardware structures: in the left side of figure it is depicted the developed embryonic machine (bio-inspired controller) with its array structure, and in the right side, the controlled system represented by a servomotor.

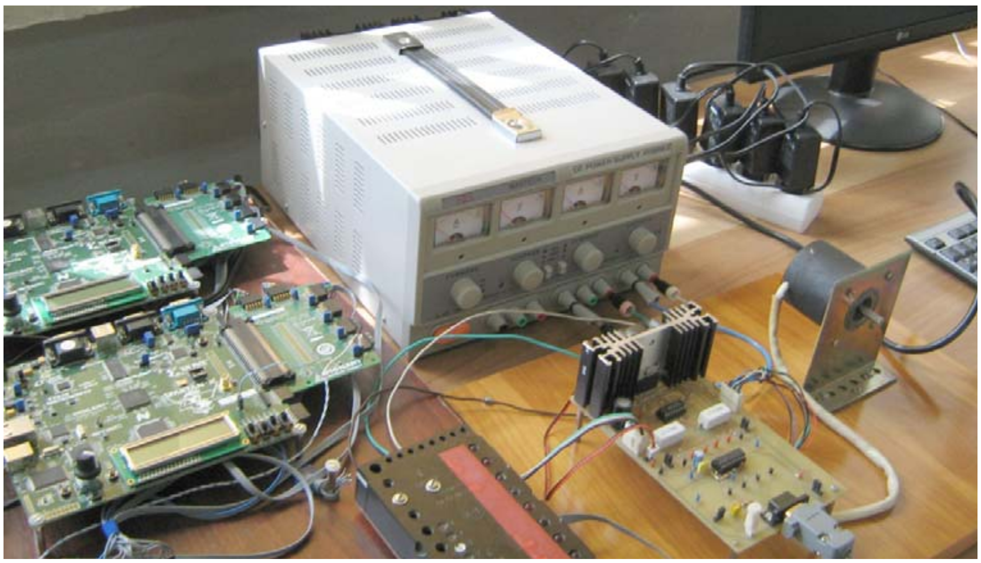

Fig. 67. The experimental laboratory setup

No other functions or tasks are executed by the embryonic machine, just the regarded network communication abilities and specially developed fault-tolerance algorithms, in order to reproduce artificial hardware immune system behaviors. All auxiliary functions or drivers like interfacing, initialization, or data acquisition are processed by the supervisor digital control system, built on a personal computer and PIC18F4550-type microcontroller. The above presented structure can be also used with success in a wide range of mechatronic applications as well [89, 90, 91].

4.4. HUMAN-COMPUTER INTERACTION TECHNLOGIES IMPLEMENTATION IN COMPLEX ELECTRICAL DRIVE SYSTEMS

In the last several years human-computer interaction technologies implementation in electrical drive systems gains an important role. This research effort has been supported by the HuComTech TÁMOP 4.2.2-08/1/2008-0009 project, founded by the European Union, the European Regional Development Fund, and the European Social Fund. The granted amount was supported by the European Union and the Hungarian Government. The results of the research have been published in the papers [94, 95, 96, 97]. In the followings a short summary of the most important theoretical and experimental achievements regarding the robotic systems multimodal communication development and implementation will be synthesized.

As it is well known, multimodality is a very common task in the human-robot communication. Human conversation is also multimodal, and a great amount of research is done worldwide to engine novel robotic systems embedding more and more intelligence for human gestures or speech recognition abilities enhancement. According to a general rule definition, multimodality enhances the richness of the communication and interaction and allows more complex information to be conveyed than is possible with a single or two modalities [98]. Human's communication is considered multimodal, since they use their hands, head, gazes, or their face to express complex information, including their current emotional status. They also can express its agreement or disagreement status, or even intentions about their next actions. Similar to everyday interaction among humans, recent trends of modern human society show a highly increased demand for human-robot multimodal interaction, to meeting a large scale of learning, social, or industrial purposes [99, 100]. Multimodal human-robot interaction and communication is an important area of robotics research and a great amount of research effort is developed worldwide to devise such a kind of "virtual humans" or human-like agents with artificially embedded abilities to perceive their neighbor environment, to display intelligence, and to interact with a human factor [101-106]. There a clear distinction is made between human-computer and human-robot interaction, this latter outstands allowing key properties such embodied systems to utilize physical environment and mobility [98, 108].

The great majority of human-robot communication behaviors are implemented on mobile agents, or so called pervasive mobile robots, endowed with complex interaction abilities. Such mobile systems are capable of emulating human behaviors in terms of communication even through verbal and facial expressions. Ideally suited, pervasive robots they should understand spoken language, recognize facial expressions, to understand human gestures, or to fully support human-friendly interaction [108]. Consequently, human-like communication and interaction is desirable, and implementing most of the human senses and communication channels is a basic condition to design and experiment intelligent, cooperative, and user-friendly service-robots. If the robot is endowed with powerful hardware resources, including multiple analog/digital communication channels, high fidelity sensors, a large amount of memory storage capability, or high speed computation units, the multimodal communication strategies implementation is highly facilitated, and the robot becomes suitable to exhibit more intelligence and additional cooperativeness in its behavior. There is the developmental and approach level where this research proposes substantial research contribution, and presents a novel design solution, supported by experimental results, obtained using the NI SbRIO-9631 prototype mobile robot system manufactured by the National Instruments Co (fig. 68).

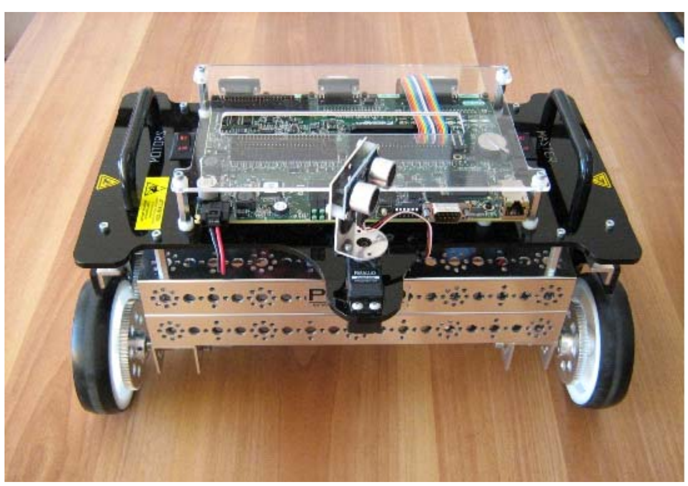

Fig. 68. The NI SbRIO-9631 prototype robot

This is a four wheeled autonomous robot which moves on smooth surfaces, whose control board is built around a Xilinx FPGA processor type. The electro-mechanical device's motion is assisted by two DC servo motors, of which the axis is interfaced with incremental pulse transmitters - through geared mechanical transmission – to measure the motors' turning positions and velocities. The motors are controlled by means of power electronic converters. It is important to mention that the orientation of a robot is obtained by the ultrasonic distance sensor, which locates the nearest obstacles and depending on the received information, the central unit performs a corresponding function.

The first step of development is to achieve a multi-modal communication connecting a NI-9234 type data processor board, through its an analog input channel a high-sensitivity *GRAS 26CA* type microphone is attached. These two additional devices are show in figure 69.

Fig. 69. The NI-9234 data acquisition card and GRAS 26CA type microphone

The NI-9234 card contains a maximum of 4 analog input ports at a voltage of ±5V, with 24 bit A/D converters, 102 dB amplification and antialiasing filters. Each input channel is capable of operating on a 51.2kS/s sample rate. One of these channels is connected a high-quality, pre-amp GRAS 26CA microphone [109]. For the image information processing a Vision Systems NI CVS-1454 type real-time image recording unit is attached, which is capable of storage, playback and to process all the visual information which is IEEE 1394-type cameras has to offer (fig. 70). This system is capable of connecting a maximum of 3 external cameras, but at the same time provides Ethernet network communication options and can be connected to RS-323 serial port and to VGA output [110].

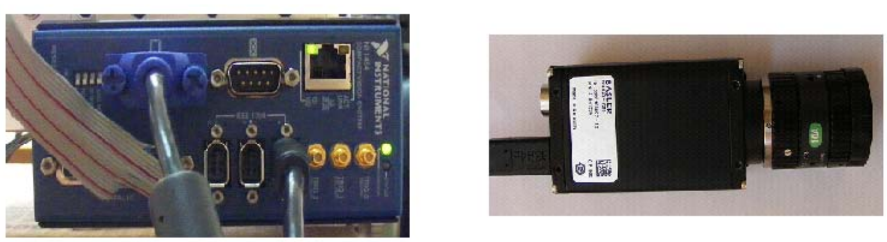

Fig. 70. The CVS-1454 Vision System module and the Basler ScA-640 camera

The network connection between the CVS-1454 Vision System and the computer allows the test results and status information to be displayed and the default settings of the devices. The Basler ScA-640 camera is an essential part of the system by supplying the image information for the device. The image processing module communicates with the robot using its output ports, uploading the robot with the results of the processed images. By interconnecting the above mentioned two devices a high speed and high quality image processing system is obtained, with the help of which complex real-time robot control can be achieved in a relatively short time [94]. Practical implementation of the NI-9234 data acquisition module begins with the interconnection to the SbRIO-9631 robot's second *C* type general purpose communication channel main board, then the microphone's connection follows to the NI-9234 card's first input.

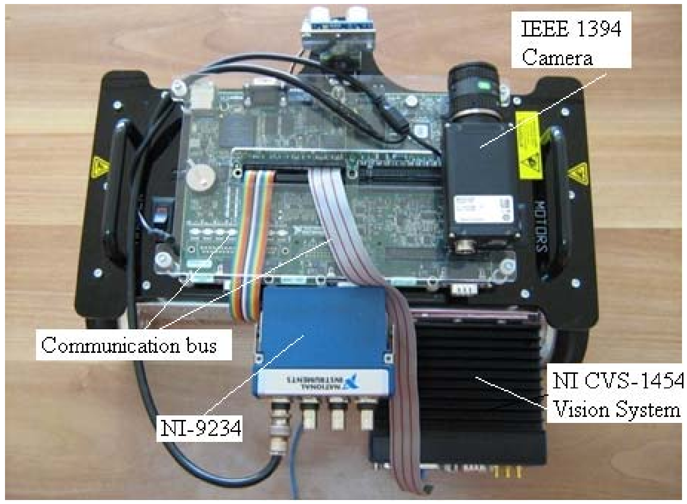

Fig. 71. The development system built on NI SbRIO-9631 prototype robot [94]

With adequate programming of the LabVIEW Robotics software package, the connected interface based on initial setup parameters will be immediately acknowledged and processed by the control board.The NI CVS-1454 image processing system is connected via the bus system of the SbRIO-9631mainboard's digital input/output. However, the FPGA processor's input/output communication lines to designate and configure in the virtual device modifications has to be carried out, inserting those two input bits, through which the information is then read (Port6/DIO8and Port2/DIO5), as featured in figure 72.

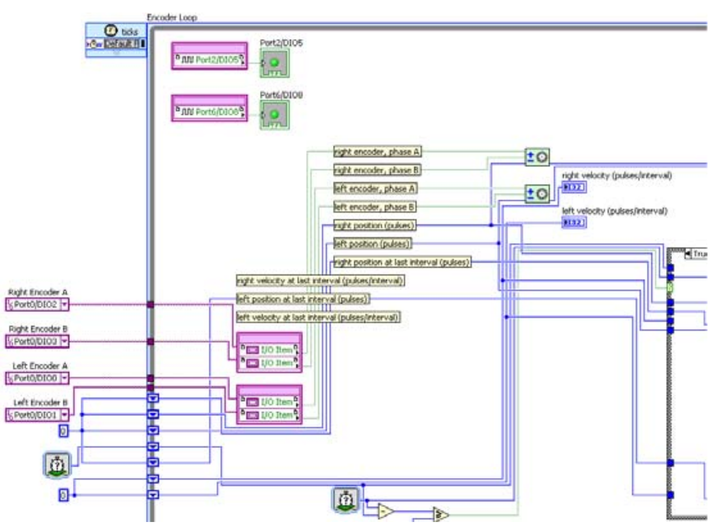

Fig. 72. The SbRIO-9631 controller card's virtual device programmer [94]

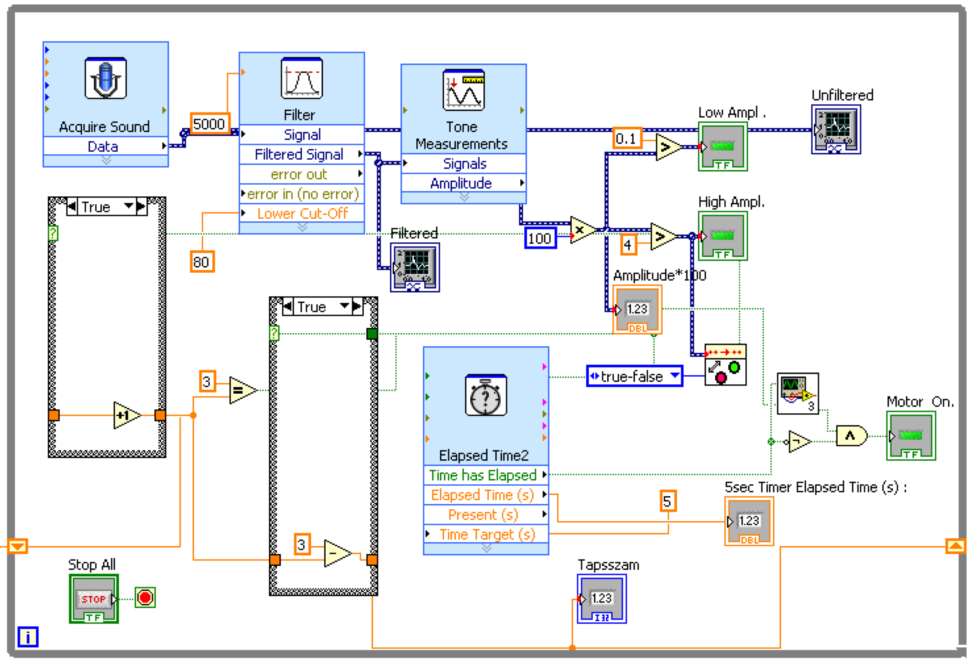

Fig. 73. The robot is controlled using a virtual device sound scanner [94]

The most complex task is the audio and video processing units' connection and after the correct programming for their operation, a design of a real-time application and experimentation to test the robot's control in the LabVIEW Robotics development environment [94]. Such a control program tested in the laboratory is illustrated in figure 73 through the presentation of a virtual device.

In the next stage the sound signal processing and control logic virtual device (VI) has been developed itself, as show in figure 74 [95].

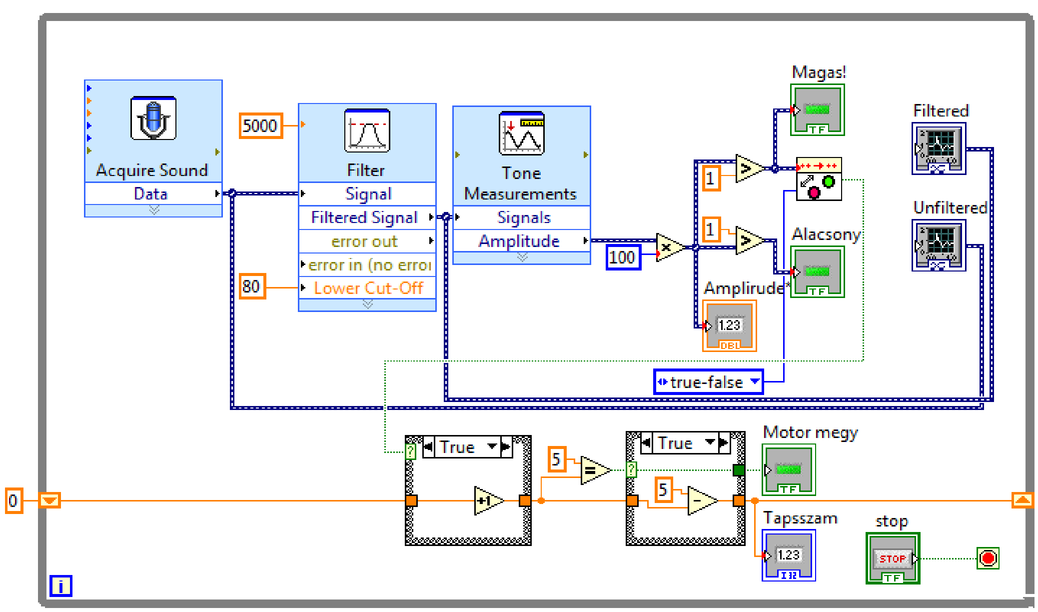

Fig. 74. Sound signal processing virtual instrument [95]

The development system built on NI SbRIO-9631 prototype robot was experimented on the laboratory stand seen in figure 75. Here the SbRIO-9631 robot is communicating by using a standard Ethernet cable with the personal computer, on which the LabView programming environment is running [95].

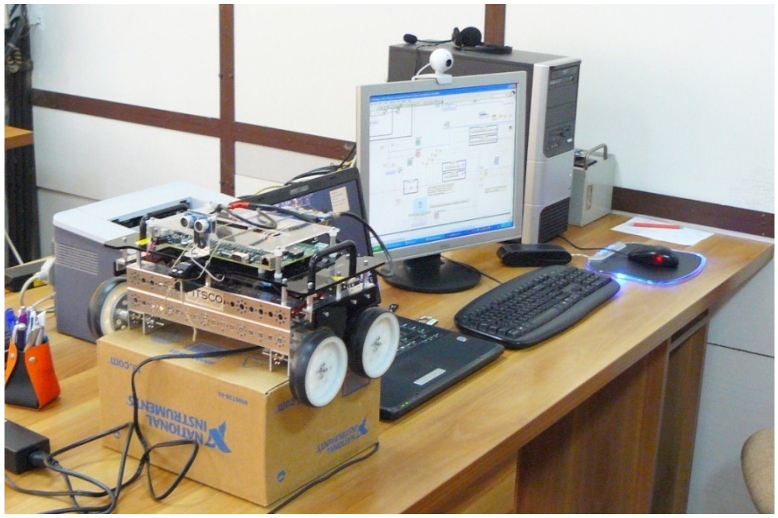

Fig. 75. The laboratory development system for experiments [95]

The robot has its own network identification number through which the remote control application by sound signals can be uploaded. When the connection is interrupted and the upload succeeded, the mobile robot will be capable of planar self-motion [95].

The first experiments are focused on different type of voice command readings. In figure 76 a measurement result is presented in the *Front Panel* window of the sound signal reader virtual instrument, where the original sound data can be seen on the left side and the filtered waveform on the right one.

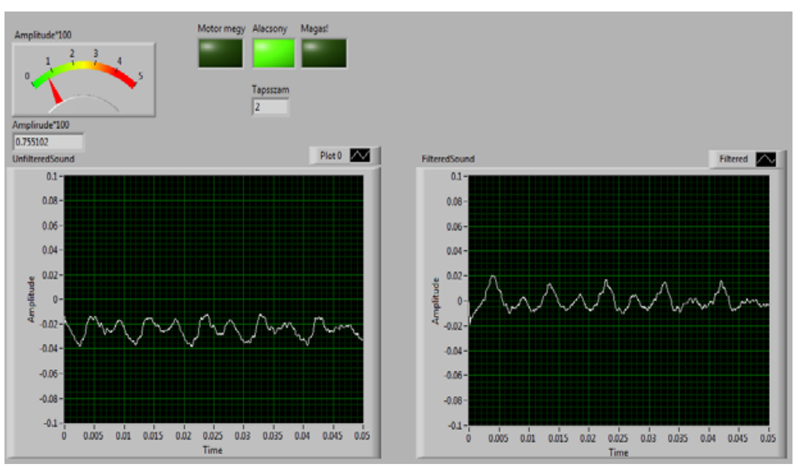

Fig. 76. Reading of a signal (rhythmic clapping) and filtering it in the Front Panel [95]

On the image a color display is visible too, which shows the change in the amplitude of the audio signal, and some LED lights that indicate if the sound reached the intensity of the threshold (if is clipping „*Yes"* then the correct logical signal is sent to trigger the mobile robots start) [95]. For more complex control words, phrases or control sentences the results can be seen in figure 77 and 78.

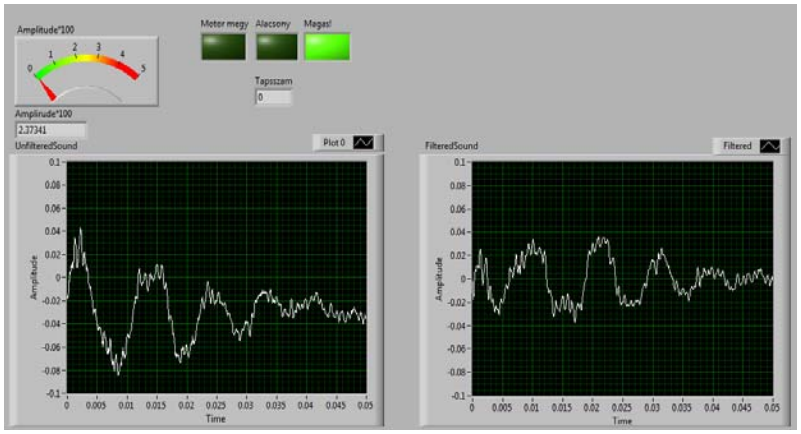

Fig. 77. Reading of a voice signal („Forward" command) and filtering it in a Front Panel window [95]

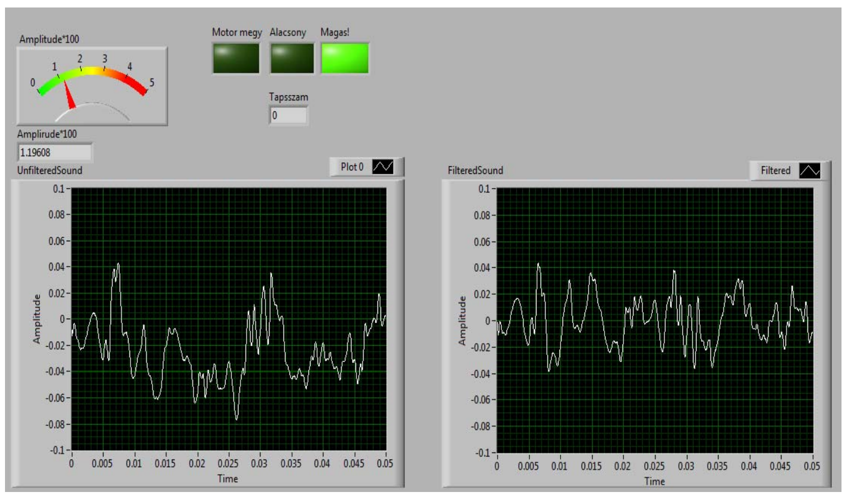

Fig. 78. Reading sentence „Hello world" and filtering it in the Front Panel window [95]

With the previous test results, the robot will perform a certain movement in the direction instructed. The image processing tasks have been programmed in LabVIEW graphical environment as shown in the block diagram from figure 91.

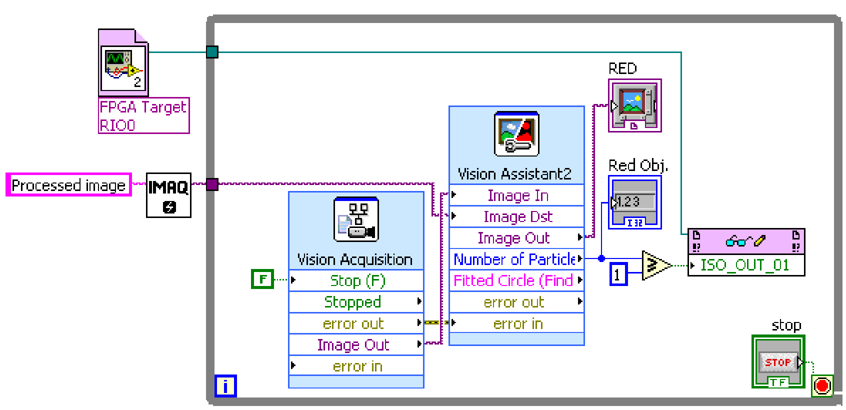

Fig. 79. The frame packages acquisition and processing virtual instrument in LabVIEW graphical environment [96]

This software toolkit has implemented two major parts: the *Block_Diagram* and *Front_Panel.* In the first window the logical programming of the components is accomplished using pre-built graphical modules, which are connected through a well-defined digital logic. In the *Front_Panel* virtual gauges, indicators, oscilloscopes, switches and LEDs are displayed, and with help of these objects accurate monitoring of I/O data becomes possible [96].

The main objective of the research efforts regarding the image processing abilities implementation is to design and develop a real-time application in the LabVIEW graphical programming environment suitable for the SbRIO-9631 prototype robot control in a way in that will be able to detect and distinguish the color and shape of objects in its surroundings and move according to these [96]. In the first steps of the development different types of shapes are shown to the robot's camera as is expressed in figure 80.

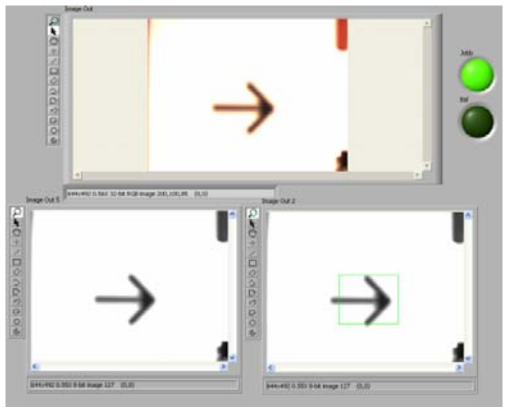

Fig. 80. "Turn right" command according to the arrow orientation [96]

In the *Front_Panel* window of the application it is easily distinguishable that the "*Go right"* command is shown to the camera with the help of a printed arrow. This information is processed then by the CVS_1454 image recognition system. The panel's right-down window illustrates that the object is recognized through by clipping a green square and the robot will move according to this information. A lighting a LED indicates also that the command was already sent to the robot.

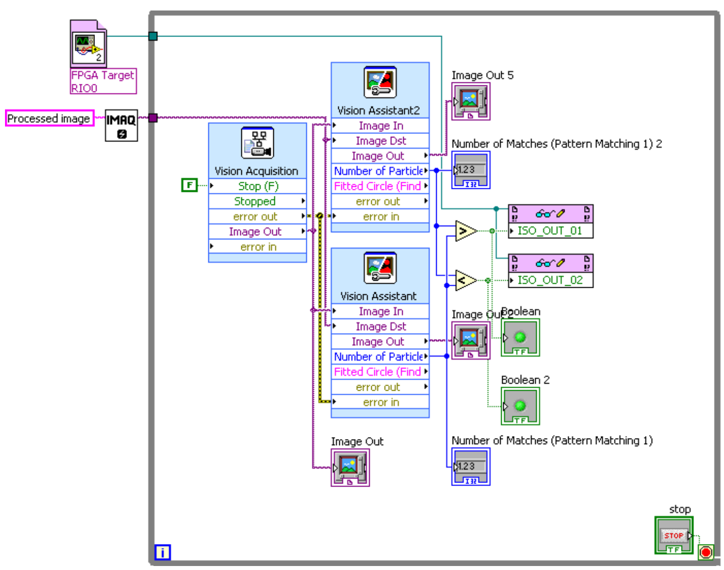

Fig. 81. Image processing: "arrow left", "arrow right" images recognition VI [96]

The LabView-based VI instrument designed and implemented to handle the *"arrow left", "arrow right"* images recognition it is presented in figure 81. Test operations regarding the image processing abilities implementation on the NI SbRIO-9631 robot unfolded in the Digital Control Systems laboratory are expressed in figure 82.

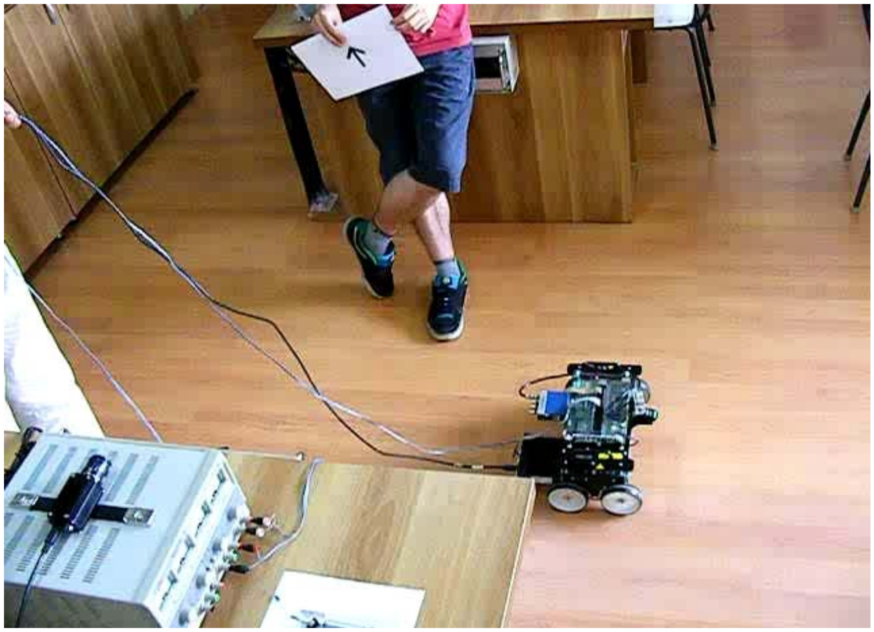

Fig. 82. Testing the robot's image processing abilities in the laboratory [96]

One other important task refers to the NI SbRIO-9631 mobile robot colors distinguish abilities implementation. In figure 83 are presented the laboratory experiments regarding this research step, by showing to the robot's camera different colors (green or red in this case).

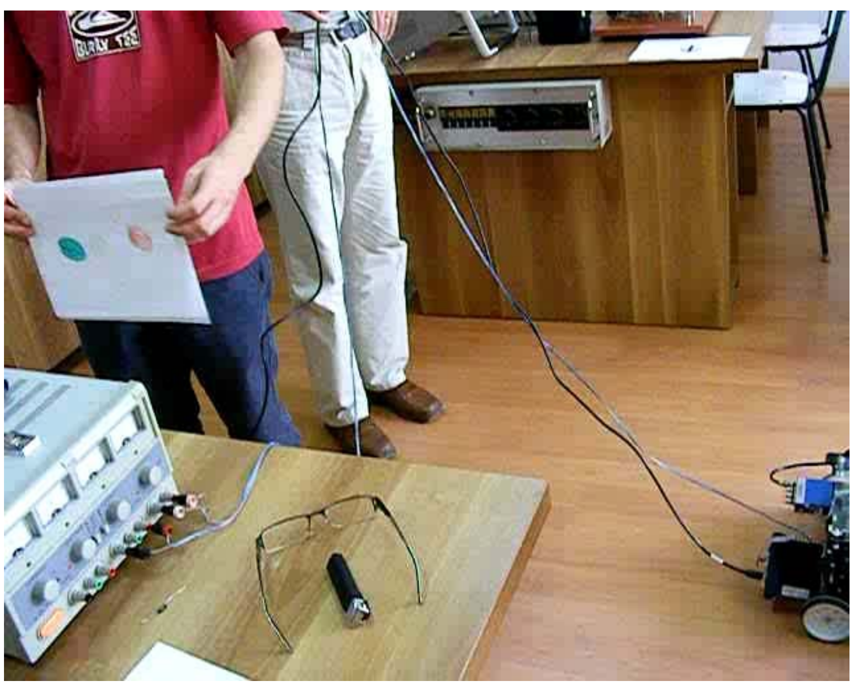

Fig. 83. Testing the robot's colors distinguish abilities in the laboratory [96]

Fig. 84. "Left-right turn" tracking the head movement [96]

Fig. 85. Testing the robot's head movement tracking abilities in the laboratory [96]

The application becomes more complex by adding not only shape tracking but face recognition too. Figures 84 and 85 shows how is possible the robot control using head motion. If the head is facing left than the software shows this by creating a green square around the persons head, in the meantime it also send a signal, commanding the robot to turn left. Similarly many applications can be created to control the robot depending on the presence or absence of a certain color or orientation of a shape. As a conclusion, it can be observed that the created complex development system is ideally suited not just for simplified educational purposes, but for complex experimental research as well. Hence, the results obtained can be used for a wide range of security-monitoring or control applications in industrial processes.

The above presented research results presented in the work: *Multimodal control of the NI SbRIO -9631 robot* has received the **National Instruments Co. III award**, for the best developments in 2012,

4.5. BUILDING MECHATRONICS AND AUTOMATION SYSTEMS DEVELOPMENT AND IMPLEMENTATION

This research topic refers to the electrical drive systems development and implementation in building mechatronics. There are included automation systems for heating, ventilation, and air-conditioning systems (HVAC) in net-zero energy buildings (NZEB). The NZEB is defined as a resident or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies. Buildings that uses non-polluting sources they generates energy onside, embedding complex HVAC systems, supervising and event monitor systems, or other complex automation systems that operates together to achieve the above mentioned net-zero energy goal are named in international references as “intelligent buildings” [111]. An example of an intelligent building infrastructure is given below in figure 86.

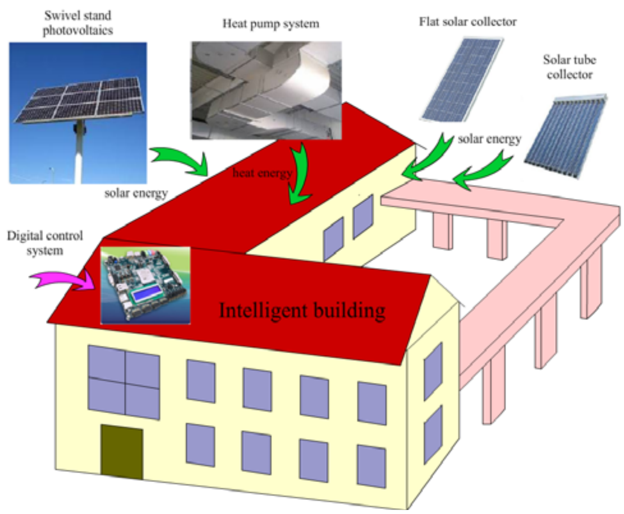

Fig. 86. Intelligent building infrastructure developed at the Building Mechatronics Research Centre, Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University.

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 [112]. By using net-zero energy strategies, it is proposed that the yearly energy consumption of the building to be fully covered from the above mentioned locally available renewable non-polluting energy sources. There one of the used renewable energy sources is the locally available solar energy captured by using flat solar energy collector and solar tube collector batteries installed on the building’s back terrace and from a swivel-stand photovoltaic battery mounted in the building’s garden shown in the figure. Additionally, a high capacity heat pump system will provide heat energy stored in several hot water tanks mounted in the intelligent building’s basement. There in the building’s ceiling has been mounted the duct system with the adequate pipes, and into a cupboard are fixed the heat pump’s condenser, the evaporator, the expansion valve, and the compressor [111, 113].

Store elements such as water tanks, liquid reservoirs, or gas containers are basic elements in HVAC systems development and implementation. In figure 87 it is presented the LabView model of a buffer tank for hot water storage.

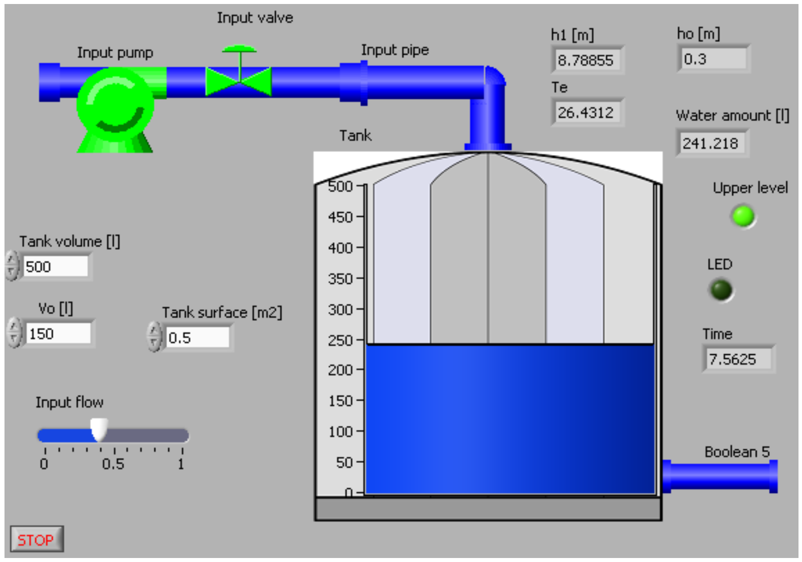

Fig. 87. The LabView model of a simultaneously filling and empting open tank in a HVAC system.

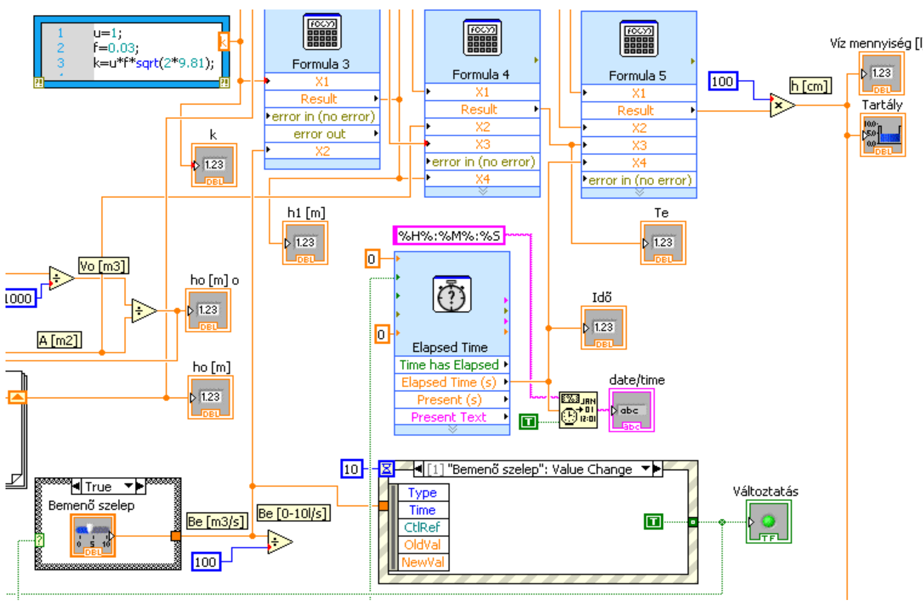

Fig. 88. The operating mode of a simultaneously filling and empting open tank in a HVAC system (a piece of the LabView Block Diagram).

A piece of the LabView Block Diagram program is given in figure 88.

The above mentioned HVAC systems embed a wide range of high performance electrical drive systems by using dc servomotors, respectively ac synchronous or asynchronous motors with their power electronic modules and the adequate digital controllers. At the same time, all the heating, ventilation, air-conditioning, or building supervising processes are controlled by microprocessor-based systems (PLCs, microcontrollers, FPGAs, etc.). In the references [111, 112, 113] are detailed presented research efforts regarding the development and implementation of such a building mechatronics and automation systems.

V. DIRECTIONS FOR CAREER DEVELOPMENT REQUIRING THE HABILITATION

As it has been mentioned in the second paragraph, the main research areas and competences are in Electrical Engineering, focused mainly in the scientific domain of the Electrical Drives Digital Control Systems development and implementation. This is a multi-disciplinary research field including and covering accurate knowledge from scientific areas such as electrical drives, electrical machines, microelectronics and digital systems, systems theory, electronics, or programming and software implementation technologies. Therefore, it supposes abilities and skills from several important scientific areas strongly linked with each other not only on the theoretical conception stage but at the implementation and experimentation research phases as well. In the last around fifteen years important theoretical and experimental competences have been gained in topics such as: pulse width modulated converters design and implementation for low-power electric motors, servomotor-based electrical drive systems development and implementation, microprocessor architectures-based digital control systems design and implementation (Intel processors, microcontrollers, FPGA processors, PLCs, etc.), fault-tolerant low-power electrical drives experimentation, or building mechatronics and automation systems implementation.

Considering the above mentioned remarks, it is expected that the future career development will follow the same area of the Electrical Drives Digital Control Systems development and implementation in Electrical engineering. This scientific domain in this case will include the following main topics:

- Pulse width modulated smart converters design and implementation for low-power electric motors;
- Servomotor-based electrical drive systems development and implementation;
- Electrical drives direct digital control systems design and implementation (Intel processors, microcontrollers, FPGA processors, PLCs, etc.);

It is expected that in the future career development higher attention and research efforts will be focused to the fault-tolerant electrical drive systems development and implementation. This research domain will be divided into the next important topics:

- Fault-tolerant low-power electrical drives experimentation;
- Biologically-inspired digital control systems development and implementation (embedding high performance real-time parallel and distributed computing hardware architectures) for critical electrical drive applications.

The main idea of this research field is that by adopting self-healing and surviving mechanisms of biological organisms from nature, it becomes possible to design complex novel digital systems provided with highly fault-tolerance and robustness properties. The goal is to imitate the biological organism’s cell-based structure which involves nearly perfect self-organization, and fault-tolerance abilities in a well organized hierarchical mechanism. Focusing on this strategy, it is expected to implement VLSI hardware structures able to reproduce biological cells or artificial organism basic functions in similar mode with their equivalents from the living world.. As it is known, the immune systems found in higher evolutional level biological organisms is a distributed and multilayered system that is robust and able to identify infectious pathogens, injury, diseases, or other harmful effects. Therefore, their properties and abilities, like self-healing or surviving, would be more advantageous in many applications, where often are imposed robustness and also high security operation requirements. Taking inspiration from biological organism's immune system and embryonic processes it is possible to acquire these fault tolerant properties in hardware circuits and to develop high reliability digital control architectures for critical electrical drives applications.

One other direction for future career development refers to the electrical drive systems development and implementation in building mechatronics and automation systems. This topic includes the electrical drive systems development for heating, ventilation, and air-conditioning systems (HVAC) in net-zero energy buildings. In international references a net zero-energy building (NZEB) is defined as a resident or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies. According to this general term definition, the essence of the concept is that by using low-cost and locally available non-polluting sources they generates energy onside, in a quantity equal or greater than the total amount of energy consumed onside in the building. Obviously, buildings that uses non-polluting sources they generates energy onside, embedding complex HVAC systems, supervising and event monitor systems, or other complex automation systems that operates together to achieve the above mentioned net-zero energy goal are named in international references as "intelligent buildings". The intelligent buildings embeds the climate control, the lighting technologies, the energy supply and its control systems, the building security and supervising systems, the doors and windows state monitoring system, the use of renewable energy sources, the internal- and external sensors, the data acquisition and data processing systems, the computer networks, the remote control systems, the digital control systems, etc. All the above ranked complex systems are linked in same way to the electrical drive systems development and implementation in building mechatronics and automation systems.

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