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Contents

Preface 5

I. Medical applications

1. Lucyna Leniowska, Rafał Pajda,
   Mechatronics in medicine – surgical robots in minimally invasive surgeries 11
2. Krzysztof Mianowski,
   Mechatronic design of gripping for a humanoid robot 35
3. Ryszard Leniowski, Marek Czujko,
   Elements of supervision and control over a wheelchair for persons with a high level of disability 45
4. Jacek Cieślik, Jakub Kasperkowicz,
   Application of CAE systems for planning surgical operations 57

II. Modelling and control

1. Dariusz Bismor,
   Fast LMS algorithm in active sound control 73
2. Paweł Kos, Lucyna Leniowska,
   Adaptive control in mechatronical systems 87
3. Maciej Walczyński,
   Application of parallel algorithms in the problem of audio and video restoration on the basis of the LMS algorithm in mechatronics 101
4. Ryszard Leniowski, Władysław Partyka,
   Simulation of complex dynamic systems 113
5. Maksymilian Sobczak, Dominik Kozik,
   Innovative concept of applications and selected elements of control and powering unmanned aircrafts 129

III. Intelligent house

1. Ryszard Leniowski, Wojciech Kogut, Krzysztof Kwartnik,
SSID – Intelligent House Control System
– selected equipment solutions 141
2. Marek Śnieżek,
Selected problems with control in a one family house 155

IV. Technological problems

1. Karol Malecha,
LTCC application
for performing microfluid systems 167
2. Janusz Lubas,
Application of TiN coatings in kinematic frictional nodes 177

Preface

The intuitive mind is a sacred gift and rationalism a faithful servant. We have created a society that honours the servant and has forgotten the gift of intuition.

(Albert Einstein)

The term mechatronics has been known for more than 40 years, however, it does not have any one sufficient definition. The reason for that, may encompass its constant development, including a more extended spectrum of science, not only in the scope of technology but also economics, ergonomics, management, marketing, aesthetics/design as well as ethics (e.g. laws of robotics).

The most common definition of mechatronics underlines the synergy of compound sciences; but other aspects are also significant, such as interdisciplinary perspective or the “philosophy” of engineering projects, used for developing products with built-in “intelligence”. Even though advanced knowledge of various disciplines and its mutual interactions constitute, undoubtedly, a solid basis of “mechatronic thinking” providing what one can do for constructors, it shall not - as noticed by Albert Einstein - underestimate the mechanisms based on creative intuition that is proper to humans only. Nowadays, there is no doubt that development of this interdisciplinary field of knowledge, which generally combines mechanic systems with modern electronics and IT, will be deciding on competitiveness and innovativeness of the industrial sector. Basic areas of mechatronics are strictly connected with the needs of the market: manufacturing and management. It is also seen in directing safety and reliability, along with an important role of mechatronic systems in automobile and aviation industries as well as biotechnology and medicine.

Civilization development relies e.g. on the fact that a greater number of tasks may be done automatically without thinking about them, and mechatronics is slowly becoming a symbol of that progress. In the 1970s, it was concentrated on servo technology in which simple implementation of technologies were connected with control e.g. where doors that automatically open or automatic focus in cameras seemed to be an important achievement.

At the beginning of the 21st century, mechatronics offer particular branches a new manner of implementing products: they do not have to possess a traditional mechanical structure, but they may be a mechatronic solution - with built-in sensors, actuators and microprocessor control. Integrated mechatronic systems, characterized by a greater level of "intelligence" and greater "independence" in the scope of solving emerging tasks/problems, with new quality of devices, providing opportunities of creating innovative technical solutions with completely new functions.

The development of mechatronics has caused it to become a significant notion in the field of engineering sciences, but its real potential cannot be assessed completely. It is still an open system of knowledge in the scope of the newest achievements of synergically integrated scientific disciplines. It may turn out to be one of the most significant achievements of our time.

Mechatronics may be popularised in various manners and it is necessary to begin with the aspect of history. It may be started from its contemporary applications and benefits resulting from that or the review of crucial construction, electronic and algorithm solutions. The second manner is sometimes more interesting, more encouraging to familiarise yourself with. I rely on this cognitive curiosity while handing you this publication. This publication includes 13 articles, divided into four sections.

The first section includes 4 works regarding medical applications. Medicine is undergoing a period of increased interest from technical sciences. Applications in the scope of biomechanics, biotechnology, biomimetics and bionics, medical robotics or telemedicine change the methods and measures applied not only in rescuing human life, but diagnosing, treating and the rehabilitation of patients as well. The synergy of the aforementioned disciplines remaining in the circle of interest of mechatronics begins to bring more and more spectacular results. The first chapter includes the review of the most important domestic and global solutions regarding medical robots, as well as presents an original structure of a manipulator, assigned for minimally invasive operations. In the second chapter, the methodology of mechatronic designing has been presented, as a result of which there is an original prototype of a hand-based grab, designed for a humanoid robot. The third chapter includes the concept of planning the trajectory for an "intelligent" wheelchair. The author's project assumes the construction of a vehicle combined with a complex IT system which would provide great autonomy of disabled persons on the basis of processed city plans with GPS marks. The fourth chapter is dedicated to several examples depicting the principles of applying Computer Aided Engineering systems in medicine. As a result, doctors obtain a new device for medical diagnosis and preoperative planning.

The second section includes 5 works on the problems of modelling and controlling in application for various mechatronic systems. The first chapter presents studies aimed at creating a modern, adaptive mechatronic system for active noise reduction, which has much potential in places of limited communication, including emergency communication. In the second chapter, the idea of creating a mechatronic system based on an adaptive algorithm has been presented. Its role relies on the active reduction of vibrations of constructive elements (panels) which may have a significant, negative impact on functioning machines and devices, deteriorating the working conditions of an operator. The third chapter is devoted to a system assigned for reducing audio and video noises. The application of Least Mean Squareshas been discussed on the basis of experiments in the nVidia CUDA environment. The fourth chapter regards broadly understood issues of modelling and connected computer simulations which are an indispensable element of the process of mechatronic designing. Also presented in this chapter is a program component developed by the authors – a “physical engine” which is part of a simulator - original software for complex simulations of dynamic systems, working in real time and characterised by a high reliability of calculations. The final chapter presents the concept of use in unmanned aircrafts, in order to increase safety coefficients of passenger flights. The solution which includes fuzzy control, assumes that one or more unmanned flying objects may become an element of another flying object, enriching its capabilities, e.g. overtaking the existing parts in emergency situations.

The third section is devoted to technological problems defined as an “intelligent house”. It includes two chapters, in which the original solutions are presented of the control system equipment layer of an “intelligent house” based on access to technologies (mechanical, electromechanical, electronic solutions) commonly known standard of data transmission as well as own solutions in the scope of algorithms and software. These solutions are characterised by a low cost of manufacturing, simplicity and openness to future modifications, according to the changing needs of users.

The final, fourth section, “Technological problems”, presents other less typical applications of mechatronic systems connected with e.g. problems of automating the determination of certain substances or providing reliability and durability of a product.

Thank you all for your contribution, I hope that this book will be needed and inspiring for readers, contributing to the development of technology, studies and innovation in the scope of mechatronics.

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I

Medical applications

Mechatronics in medicine - surgical robots in minimally invasive surgeries

Lucyna Leniowska*, Rafał Pajda*

Summary

This article presents an overview of mechatronic robotic systems used in medicine. Due to the dynamic development of this field, own classification of such systems is given with particular emphasis on robots used in minimally invasive surgeries (MIS). Some features of the individual classes have been characterised and their most typical representatives have been described. A little more space was devoted to the class of ‘medical robots’, due to the contribution of the authors in its development. In addition to the presentation of the most well-known MIS robots, their typical parameters, capabilities and limitations, the original proto-type surgical manipulator ROCH-1, which also belongs to this category, is also described.

Keywords: surgical robots, minimally invasive surgery, rehabilitative equipment, diagnostic devices.

1. Introduction

Mechatronics is a young and dynamically developing field of science and it is not possible to precisely define it. At the first stage of its development, the science was connected mainly with an industry - its role focused on the constant development and miniaturisation of structures which, in an “intelligent” manner, supported functions of available products. Sometimes they equipped them with new, functional elements. In the mid-1980s, along with the boom of automation and robotisation of different processes, there was an opportunity that emerged to use manipulators and robots in surgical procedures, which is why medical robotics was born.

Surgical robots are highly technically advanced mechatronic systems, used during the performance of operations as “intelligent” auxiliary tools. Observing the progress in this young branch of medicine, it may be noticed that the first generation of surgical robots had been installed from the 1990s in operation rooms all over the world.

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Robotisation is being gradually introduced in all surgical wards, but also in rehabilitation or diagnosis divisions as well.

One of the main goals for teams that undertake the construction of robots for medical applications is to create a system which may be used in minimally invasive surgeries (MIS). This revolutionary approach to operations is possible e.g. by means of robotised tools, and allows for precise procedure performance by relatively small incisions on the body of the patient. As a result, there is minimal trauma and damage to new tissues and the recovery period is greatly shortened.

There are many classifications of robotised medical systems but from the viewpoint of mechatronics, the most significant factor seems to be a division due to the tasks which may be performed by a robot in an operation room or during treatment. These tasks were classified in 1998 by Taylor [13] in the following manner:

- medical robots superseding surgeon's assistance,
- remotely controlled surgical telemanipulators,
- navigation aid systems,
- precise positioning systems,
- precise motion systems.

Currently, the main developmental tendency of the miniaturisation of solutions and creating micromechanical systems is strictly connected with electronics and control algorithms. New technologies emerging in the scope of microsensorics and microdrives allow developing innovative structures of robots which change the image of surgery, contributing to:

- shortening the recovery time of the patient by means of decreasing posttraumatic injuries along with a miniaturised structure of tools,
- improving the safety of the procedure by means of the monitoring system and medicine dosage,
- improving the precision of the performed procedures by means of a built-in trajectory and stabilisation system (reduction of hand vibration),
- faster and adequate diagnosis of conditions,
- developing simulators allowing for performing a virtual test of the planned procedure,
- allowing performance of surgical procedures from a distance.

Moreover, mechatronics supports other areas connected with medicine that we may differentiate:

Area 1. Mechatronics at a manufacturing level Includes notions connected with automation of processes and technological lines applied in the pharmaceutical industry. This constitutes as an area of interest by technologies as well as specialists in the scope of industrial automation.

Area 2. Diagnostic devices Advanced mechatronic systems aimed at performing certain specialist studies or analysis, in a semi-automatic or automatic manner.

Area 3. Rehabilitation and supporting devices Mostly robotised, equipped with feedback, assigned for supporting the rehabilitation of patients and automatic progress check-ups in reconstruction or restructuring tissues. Exoskeletons are an advanced kind of rehabilitation system. They constitute extended mechanical systems equipped with sensors, actuators and control systems. The main task is to reinstitute motoric capabilities of patients who, due to the diseases of muscular tissue, have problems with self-moving. These devices also include automatic wheelchairs as well as rescue robots.

Area 4. Mini- and microrobots The conception of this family of mechatronic devices are applied in the patient's body without any incisions (e.g. orally). These miniature structures are equipped with an autonomous power supply, a gripping system, sensors and medicine applicators that are capable of moving into the affected organs, providing substances, supporting treatment, or monitoring.

Area 5. Advanced prosthetics It includes complicated mechatronic and biomechatronic devices directly cooperating with a human organism. The example for that may include an insulin pump, artificial heart, hearing, sight and bone implants or other structurally advanced prosthesis constantly cooperating with human organisms.

Area 6. Medical robots These devices use the achievements of robotics. Their application is connected with minimally invasive surgery (MIS) and neurosurgery. The most frequent function of these devices is positioning a surgical device with greater precision than a surgeon. Greater and greater significance is placed on the implementation in the methods of planning trajectory of approaching and departing devices, introducing remote operations, performed by the surgeon operator being beyond the operation hall or monitoring and archiving cases. Its particular advantage is the capability of constant operation consulting by specialist dispersed in various centres, for example in the form of a teleconference or even undertaking such procedures by other experienced operators.

The aforementioned division of mechatronic systems applied in medicine is presented in a graphical manner in figure 1.

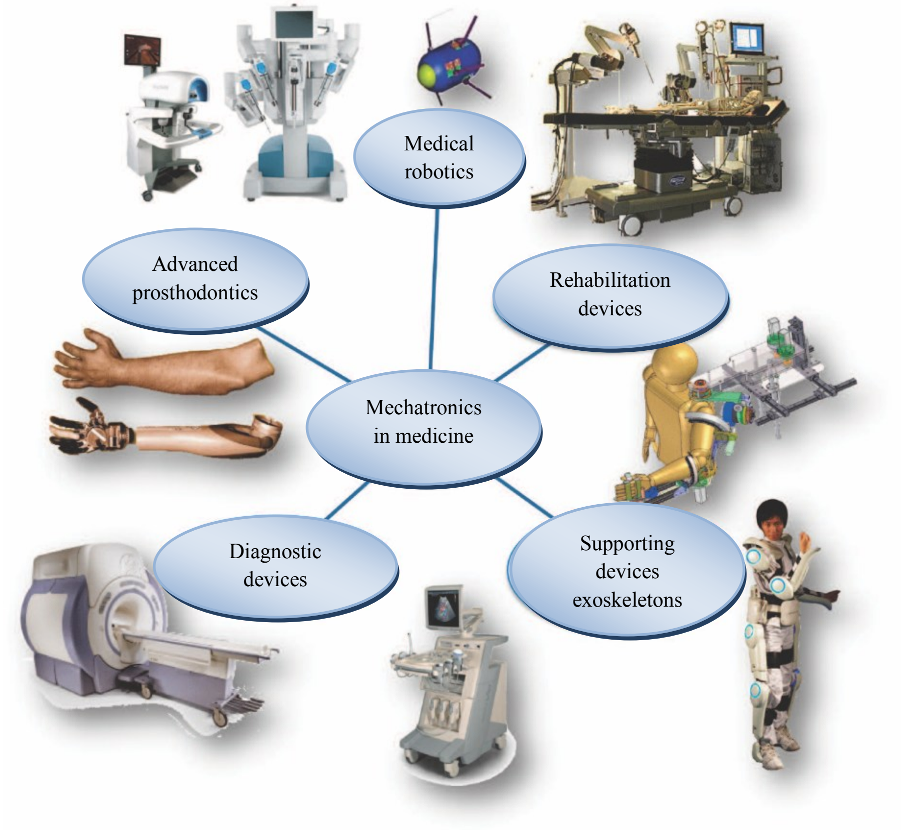


Fig. 1. Main areas of applying mechatronics in medicine
[17, 18, 19, 20, 21, 22, 23, 41]

The aforementioned groups have been described as follows.

2. Mechatronic systems applied in medicine

Medicine is undergoing a period of increased interest from technical sciences. Applications in the scope of biomechanics, biotechnology, biomimetics and bionics, medical robotics and telemedicine change the methods and measures applied, not only in rescuing human life, but diagnosing, treating and the rehabilitation of patients as well. The synergy of the aforementioned disciplines remaining in the circle of interest of mechatronics begins to bring more and more spectacular results.

2.1. Diagnostic devices

Contemporary medicine uses technical devices that support the work of medical personnel. Automated diagnostic systems perform studies faster and efficiently support the interpretation of its results. It turns out that the skills of a physician, supported by knowledge and experience, are not always sufficient to precisely diagnose the condition of a patient. The natural stage of medical development was the introduction of new measurement technologies and result analyses. An example of a commonly used system in the contemporary world is the CAT scanner.

Fig. 2. BrightSpeed16 [30] Tomograph

The device performs screens of different sections of a patient in order to make a comparison. The very first tomograph was built in 1968 by Godfrey Newbold Hounsfield in Great Britain. The possibilities of this instrument were not great; the examination lasted 25 minutes and it took about 2.5 hours to process the detectors, which were only able to produce images with a resolution of 80 x 80 px.

Modern CAT scanners are mechatronic devices with a very complex electromechanic structure, but they have extended software for processing the obtained images. Currently, it is possible to recreate virtual models of particular organs in the human body on the basis of imaged intersections obtained by the CAT scanners and the proper software, e.g. OsiriX [28].

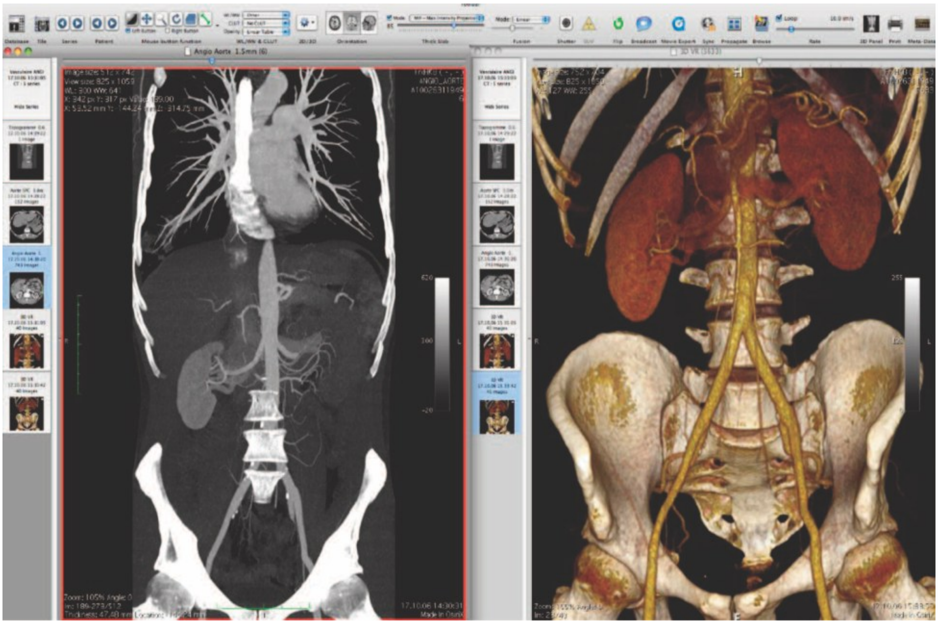


Fig. 3. The 3D model of a human body reconstructed using CAT layer images in OsiriX [28]

The newest achievements in the field of CAT scanners are HRTC scanners, which are able to produce 3D images with high resolution within layers below 1 mm. A CAT scanner is not the only example of an advanced mechatronic system applied in medicine. In diagnosis, there are many other electronic and software assisted devices (MRI, USG, densitometers, etc.). According to specialists, in the near future it will possible to perform completely automated examinations during a medical appointment or a surgery. Advanced scanners will rapidly obtain a range of information. The analysing algorithms will determine probable sources of disorders which will be compared with a database and will allow diagnosing symptoms and defining the most adequate methods of treatment.

2.2. Rehabilitation and supporting devices

Effective rehabilitation requires time and cooperation with an experienced rehabilitant. In many cases, access to a good specialist is difficult and the time of cooperation is too short for the effects of the procedures to be visible. That is why there is a need for creating mechatronic devices functioning as a personal rehabilitant for the disabled. First studies in this area emerged more than 25 years ago. In 1995 was the first presentation of the conceptions of applying an industrial robot for rehabilitation of patients called REHAROB [3]. A similar system was designed by Polish scientists from the Industrial Research Institute for Automation and Measurements (fig. 4b).

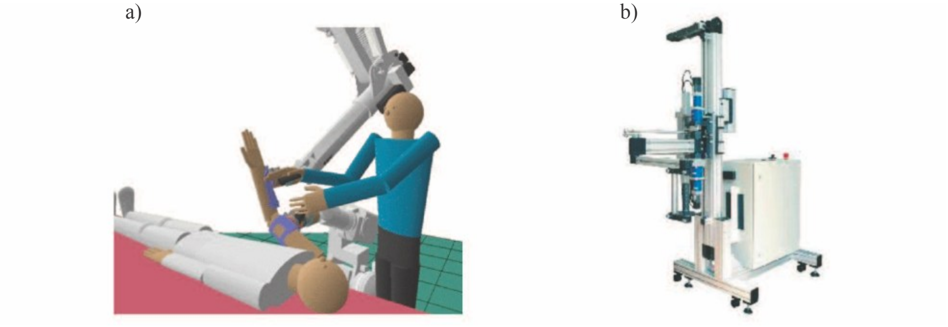


Fig. 4. a) The rehabilitation robot REHAROB developed at the University of Technology and Economics in Budapest [19]; b) RENUS-1 Mechatronic system of motoric support for persons after cerebral stroke developed at the Industrial Research Institute for Automation and Measurements [20]

Figure 4 presents two mechatronic rehabilitation robots designed to help regain movement in an arm. Both devices allow passive or active multisurface movement for upper limbs. It should also be mentioned that there are two completely new solutions aimed to reinstitute full motoricity for the whole body of a patient. This is accomplished by using exoskeletons as an external structure, mounted to the body with straps. Military applications of said exoskeletons helped accelerate their development. There are many companies concurrently competing to obtain a contract for a new area in the military market.

2.3. Mini- and microrobots

Miniaturisation of electronic and mechanic elements made way for the development of a completely new family of mechatronic devices being applied in medicine i.e. mini- and micro-robots for the medical field. In recent years, many studies have been carried out on the miniaturisation of solutions and prototypes of minirobots. Some were even developed that may be placed inside the body of a patient. Scientist from the Laboratory of Micro and Nanophysics at Australia Monash University proposed a robot that is similar to a tadpole (fig. 5a) which would be able to move freely throughout the circulation system of a human being.

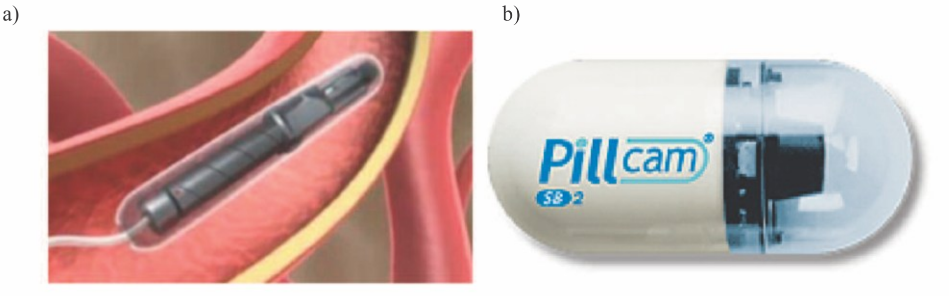
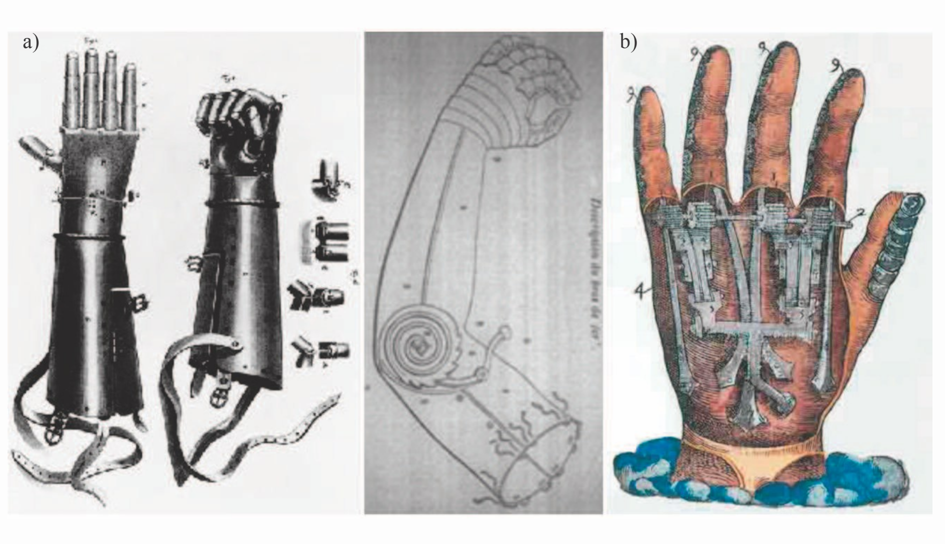


Fig. 5. a) Prototype of a robot developed at the Laboratory of Micro and Nanophysics at Australia Monash University [25],
b) Endoscopic capsule which is now applied in modern procedures [27]

These types of robots can be equipped with miniature sensory systems and cameras by means of which make it possible to obtain information about the condition of the patient. It may also provide a way to administer medicine in a precise place of the organism, minimising side effects at the same time. Minirobots are developing at an intensive rate, however the solutions show their unconventional and revolutionary applications. Currently, the commercially available products are such solutions as the Pillcam [27], which is a vision system that is encapsulated in a tablet and is used for diagnosing alimentary canal disorders.

2.4. Prostheses and implants

Prostheses i.e. various apparatus providing a substitute of a lacking part of the body or organ and have been around for many years. The first traits of such solutions date back to ancient times. They are widely selected for aesthetic purposes (artificial nose, eyes, breasts) or for functional purposes (orthopaedic prostheses).



Rys. 6. a) Metal prosthesis carried by Götz von Berlichingen [24]
b) Ambroisa Pare’s prosthesis design 1564 [31]

Prostheses, formerly built from such materials as: wood, metal, and leather, are now complicated devices including complex systems of sensors, executive and control elements, which make it possible to regain natural human movements to a greater or lesser extent. In the following solution presented by *Touch-Bionics,* the motor is comprised of a BLDC engine, however, to steer the prosthesis a measurement system is applied which reacts by using miosignals. Miosignals are received using built-in electrodes that are able to register impulses from muscle *actions* which are processed proportionally to mechanical changes in muscle fibre tensions and enables the control of the prosthesis.

Fig. 7. a), b), c) Contemporary prosthesis i-limb by Touch-Bionics [23]

The abovementioned solutions represent only a few of the many possibilities. Currently, several research institutes all over the world are working on the modernisation of advanced prosthetic functions [1]. The most advanced prostheses allow mechanic and sensory integration with the human body by means of new biomimetic techniques. In cardiosurgery, heart valve and vessel prostheses are widely used (artery and vein prostheses) and in otolaryngology - implants i.e. advanced electronic devices, implanted during surgical operations for people with deafness or deep sensory and nerve inaudibility. The patient does not obtain physiological hearing, but hearing that is quite similar. The mechatronic approach to designing these kinds of devices provides wider capabilities of developing smaller, more effective and controllable products, allowing thousands of people to return to almost normal functioning.

3. Medical robots

Medical robots have a great potential and constitute a great solution for designers as well as for surgeons [14]. They include the precision of movements and allow minimally invasive access to operated areas. Currently, the applied robots are mainly telemanipulators, by means of which a surgeon can make decisions regarding movements and tasks by standing at a console, while a proper effector implements these tasks at a given work area. The division of robotised surgical systems was validated in 2006 by Z. Nawrat in the following manner [9, 10]:

1) Robots substituting assistants who hold the endoscope during an operation.
2) Surgical robots - telemanipulators.
3) Navigational robots (passive) - are used to precisely position and maintain the proper course of the tool.
4) Navigational robots (active) – work as executive tools in the system of copying the trajectory defined during preoperative planning.

The most common instruments are described below.

3.1. AESOP

The AESOP (*Automatic Endoscope System for Optimal Positioning*) was manufactured by Computer Motion Inc., California, and is the first robotised 'assistant' system accepted by the FDA (*The Food and Drug Administration*) and was permitted to work surgically in 1994. The functioning system is limited to automated manoeuvring and positioning the endoscope camera, which in turn requires one less person needed for assistance. Concurrently, the system allows the increased reliability of positioning the camera, and mostly eliminates the vibration of an image, which used to be problematic during long procedures. The control system allows constant positioning by means of voice orders. The controller allows designing a given movement trajectory. Due to the numerous advantages, the system has become one of the mostly used robotic assistants and still functions as support for ca. 1/3 of all surgical procedures performed worldwide when using minimally invasive techniques. Since 2000, the AESOP 3000 medical robot has been used clinically in Poland. The Cardiosurgical Clinical Complex at the Silesian Medical Academy in Katowice, under supervision of prof. A Bochenek, has performed ca. 250 operations using this device [11].

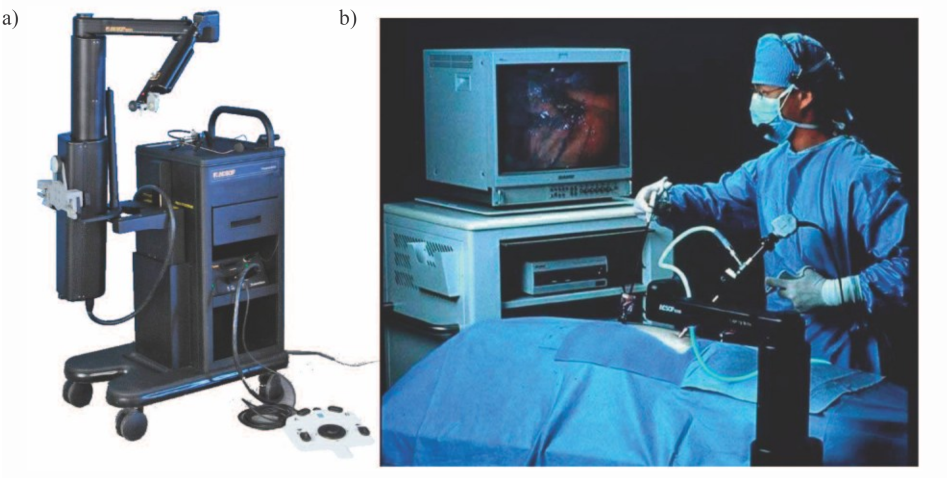


Fig. 8 a) AESOP system with the control box [32],
b) AESOP during a procedure in an ER [33]

3.2. EndoAssist

EndoAssist is a manipulator which, similarly to the AESOP, is used in endoscopic procedures. Contrary to the previous solution, the arm control is performed by means of a specially designed joystick and pedals. The newer version of the robotised 'assistant' was improved in regards of the construction as well as it has been equipped with a new type of positioning transmitter, installed on the forehead of the surgeon. The transmitter has a built-in gyroscope and accelerometers which allows changing the motions of the surgeon into subtle changes in positioning of the endoscopic camera. From the viewpoint of a control nature, this attitude seems like an optimal solution. The advantage of the *EndoAssist* system over *AESOP* relies on positioning the camera better and does not require any additional learning processes for the voice recognition module. Thanks to that, the manipulator may be prepared for work within several minutes, eliminating any language barriers.

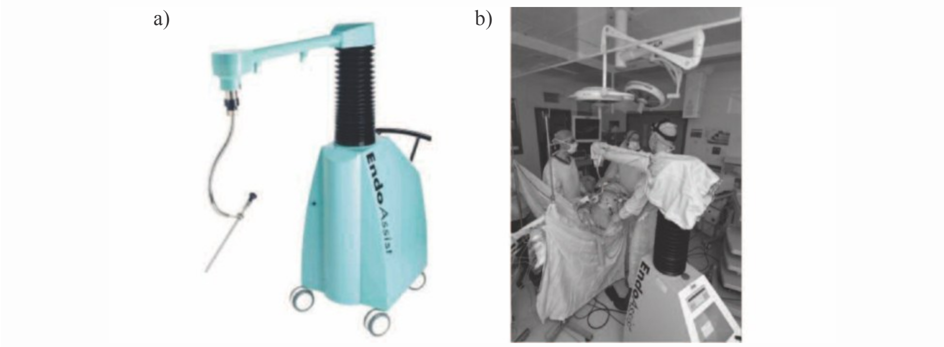


Fig. 9. a) EndoAssist System [34], b) EndoAssist during a procedure [35]

3.3. PathFinder

Some types of procedures e.g. in the scope of neurosurgery, requires such precision that the surgeon is not able to perform them without specially robotised positioning tools. It should be emphasised that the estimated precision of a manual procedure is ca. 1 mm. During procedures directly to the brain, this precision is insufficient as any mistake may cause irreversible damage. One of the robots used in neurosurgery is the PathFinder. The system is made of a surgical arm, consisting of the positioning tool which uses layer images from the CAT scanner. This positioning system defines the optimal path to reach a specific point in which e.g. a biopsy must be performed. This procedure is possible to be conducted in an automatic and manual manner. There are special markers placed on the surface of the patient’s body, which is registered by the cameras to allow for the tools orientation.

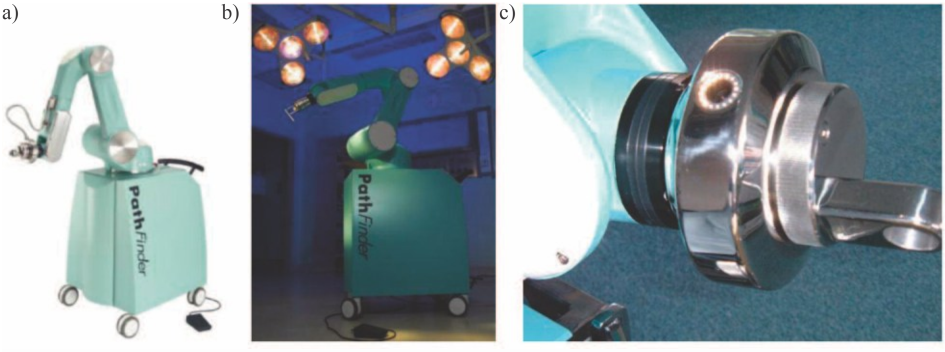


Fig. 10. a), b) PathFinder surgical robot,
c) Positioning effector with a visual system and light source [8]

3.4. Da Vinci

The Da Vinci telemanipulator is the most known and technologically advanced solution. It is mostly used in hospital practice, and is a robotised surgical system that supports human operations. It was developed by an American company, *Intuitive Surgical,* and is characterised by high precision, low invasiveness and a user friendly, intuitive interface. The surgeon performs a procedure sitting at the control console at a distance from the patient, equipped with a monitor and ergonomic control tools. The image is passed by an endoscopic camera divided by separate optical canals which provide a real three-dimensional view of the operating field through binoculars at the control console. It allows easy operation of the visual field (slide, turn, magnitude etc.). This image is also specially developed, filtrated and optimised in order to obtain the best quality. The second most significant element of the Da Vinci system is the platform with arms, positioned in the operating hall in the immediate neighbourhood of the patient. The platform has four robotised, electromechanical arms, among which, three are equipped with surgical tools and one supporting an endoscopic camera.

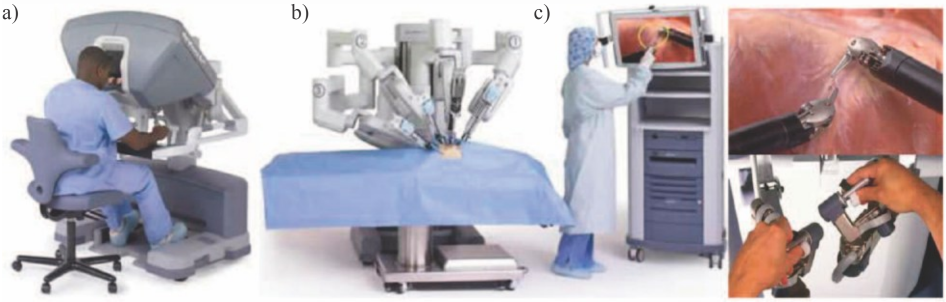


Fig. 11. a) Control console,
b) Arm system; c) Levers of the transmitter and working tools [36]

To complement the system, there are a set of patented EndoWrist® surgical tools that are mounted by special interfaces in the arm grips of the platform and moved remotely by the surgeon [36]. Currently, there are more than 2000 robots working worldwide, performing hundreds of thousands procedures annually. The greatest number of tools operate in the USA, however, in Europe, the countries that use it the most are the Italians and Germans (more than 50 units). In December 2010, at the Provincial Specialist Hospital in Wroclaw, the first Da Vincin surgical robot was launched in Poland. It was possible thanks to the attempts of the Hospital Director, prof. W. Witkiewicz [46]. The robot is used by surgeons, gynaecologists and urologists. In the period from December 2010 to November 2011, there were several operations performed with its assistance.

3.5. Zeus

The Zeus medical robot is second, due to the frequency of use in hospital practice. It is a remotely controlled robot that is applied in minimally invasive surgeries. It was manufactured in 1999 by an American company *Computer Motion Inc*. In 2001, it obtained the acceptance of the FDA *(Food and Drug Administration*) to perform minimally invasive operations in the USA.

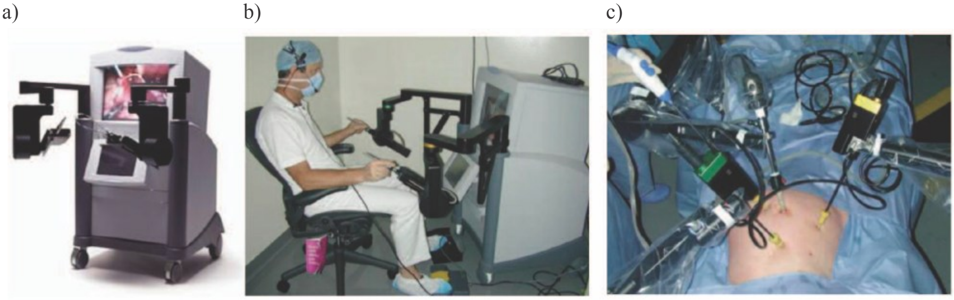


Fig. 12. a) Control panel for the Zeus robot [37], b) Work using the panel, c) Typical layout of the manipulators [12]

Zeus is composed of three interactive arms mounted on the operating table, computer controller and ergonomic surgeon's console. One of the arms is a voice order positioned endoscopic camera, however, two other arms are controlled directly by the joysticks and pedals. During an operation, the surgeon sits in front of the monitor that receives images from the operating table and observes the movements of the surgical tools. The console is equipped with two joysticks, imitating the palms and wrists of the surgeon, allowing the performance of very precise movements. As a result, it directly eliminates the effects of fatigue of the physician during a procedure. In 2003, after a long patent war between *Computer Motion* and *Intuitive Surgical*, there was an agreement, pursuant to which there was a withdrawal of the ZEUS and AESOP robots from the market. These systems are not sold commercially, however, due to a great number of implementations, there still remains spare parts and technical assistance.

3.6. Robin Heart

The series of *Robin Heart* manipulators [45] emerged in Poland at the Foundation of Cardiosurgery Development in Zabrze, in cooperation with specialists from several academic centres. In 2000, upon the order of the Foundation, the first version of the robot assigned for cardiosurgical operations was developed, which is constantly undergoing advancements. The *Robin Heart 0*, *Robin Heart 1 and Robin Heart 3* manipulators were developed at the Institute of Machining Technology at the University of Technology in Łódź, while the *Robin Heart 2* manipulator was designed at the Warsaw University of Technology. In 2007-2008, the *Robin Heart Vision* was developed, which was assigned for controlling the endoscopic positioning of the visual track. In 2008, along with the use of *Robin Heart 3*, pre-clinical studies and tests on animals were launched. The latest version of the manipulator is the *Robin Heart mc*$_2$, which was created in 2010. This is a module structure with eight degrees of freedom (3 positioning, 5 for orientation and closing the tool), controlled from the *Robin Heart Schell* console. The control system has a double measurement system. Through experiments, the cinematic parameters measured: scope of movements, resolution, and force transition, which were fully consistent with the assumptions and they allowed the performance of all planned surgical procedures. By using the *Robin Heart mc*$_{2}$, the first teleoperation experiment was completed in December 2010. The procedure, performed remotely, relied on the electroagulation of a pig heart. The console was operated by cardiosurgeon Joanna Śliwka from the Silesian Centre of Heart Disorders in Zabrze. Presently, there are other clinical teleoperation attempts that are on-going [9, 11].

Fig. 13. a) Prototype of the most modern structure of Robin Heart mc$_{2}$ [38], b) [39], c) Robin Heart Vision [29]

3.3. MIRO

MIRO is a universal robot for minimally invasive surgical operations, designed and performed at the Institute of Robotics and Mechatronics DLR (Germany) [47]. Thanks to light weight (ca. 10 kg) and parameters similar to the sizes of a human arm, MIRO does not take up much space at an operating table. The system is characterised by a complex column structure which has seven articulations, thanks to which, there is a great working space without any collisions. The robot arm is a highly integrated mechatronic system. Apart from engines and levers, it integrates at each articulation joint with sensors of torque and positions, power amplifiers, electronics and programmed logics systems. The turning solution is an application of a complicated system of measuring forces (for seven axes) by tactile sensors in the control system with feedback, which allows sensing the resistance of the tissue and has an impact on the surgeon's work.

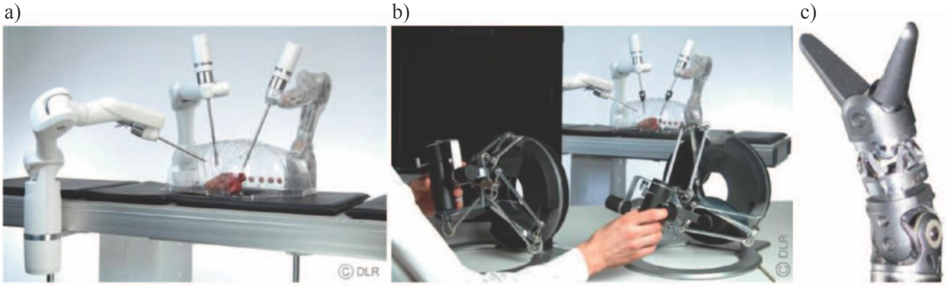


Fig. 14. a) Typical set of arm work, b) Positioning of the MIRO robot, c) Grip [40]

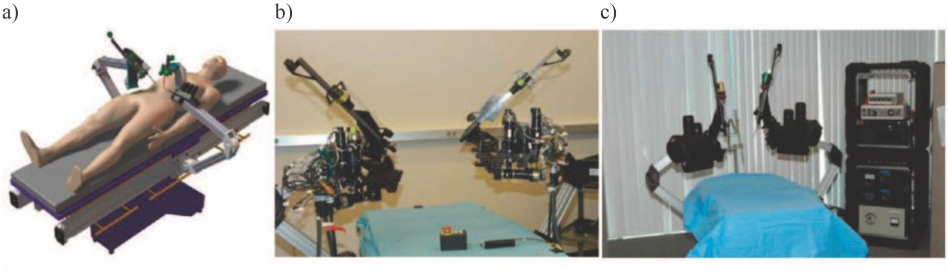
3.4. SOFIE

SOFIE is another surgical robot developed by Linda Van den Bedem from the Technical University in Eindhoven [41]. The robot consists of three arms, two of which are equipped with surgical tools, the third one, optionally, is used for supporting the endoscopic camera. The SOFIE system is designed with feedback from the forces acting on the working tool thanks to the use of tactile sensors. As a result, it gives a possibility of a more conscious operation with precise control of the pressure. The patented method of measuring forces and torque in particular articulation joints, as well as in the working ends, leads the way for a great opportunity for the SOFIE system prototype to enter the production stage.

Fig. 15. a) Computer model of the system, b) Robotised SOFIE system along with the main designer Linda van den Bedem [41]

3.5. RAVEN

The telesurgical RAVEN system was built upon the order of NASA at the University of Washington, Laboratory of Biorobotics department. The structure was engineered with a view to possibly perform procedures at a distance, with regard to cosmic space. RAVEN was designed with the use of a spherical mechanism so as to provide stationary location along with remote, wireless control, each with two arms and 7 degrees of freedom. At the testing stage, there were a set of motion transmitters applied called *Phantom Omnis* (*Sensable Technologies, USA*) [42] and a two-direction data transmission computer system.



Rys. 16. a) CAD model of the RAVEN system, b) Prototype without covers, c) Complete system with the control box [26]

3.6. Amadeus

The Amadeus robotised surgical system is a very modern structure, developed by TitanMedical Inc. [43]. The prototype has four arms, controlled by an advanced system of positioning, communication and vision. The arms have a LWR lightweight structure, developed by KUKA and weighs under 10 kg. The complex structure of the manipulator, including electrical drives and in particular, joints, allows reaching a greater working area than other systems do. Collision zones between the arms are smaller than in the Da Vinci system. There is also a very precise arm sensory system. The position measurement is doubled in each of the joints where measurements of torque and force are present. It gives a possibility of calculating and simulating actions of forces directly on the patient's tissue, which minimises the risk of damage or organ irritation. The producer guarantees that the surgeon will have the same experience as he would if he was working directly on the tissue himself. Additional benefits are the visual system. The designers decided to use the 1080p 3D HD vision technology. Image quality and its precision allow working with the system and improves the positioning of surgical tools. Amadeus also has an advanced system of communication, meeting all criteria to facilitate teleoperations.

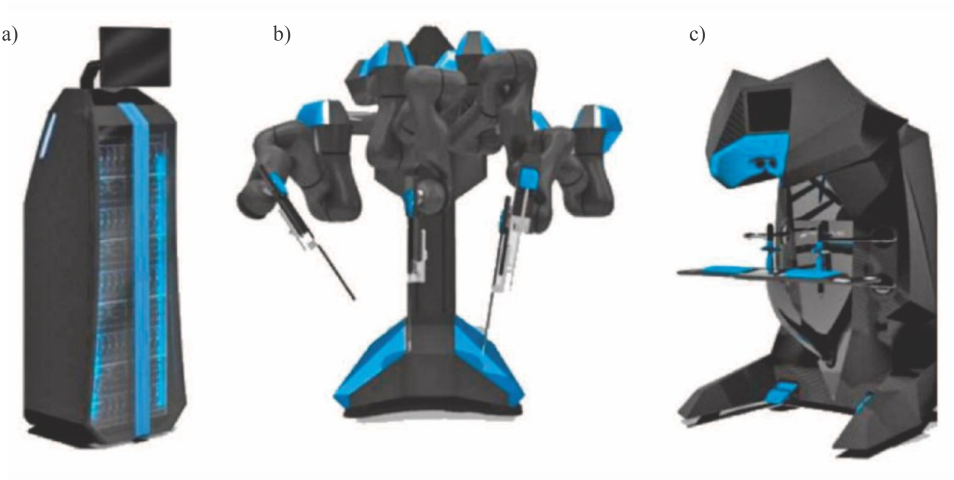


Fig. 17. a) Controller and server station of Amadeus,
b) System of manipulators, c) Control console [43]

The most important novelty in comparison to other surgical systems is the innovative, flexible terminal of the working tool which was based on the idea of a serpent (Fig.18 a). It increases the operating field, allowing (to some extent) to avoid crucial organs as well as perform operations with standard methods that have yet to be discovered.

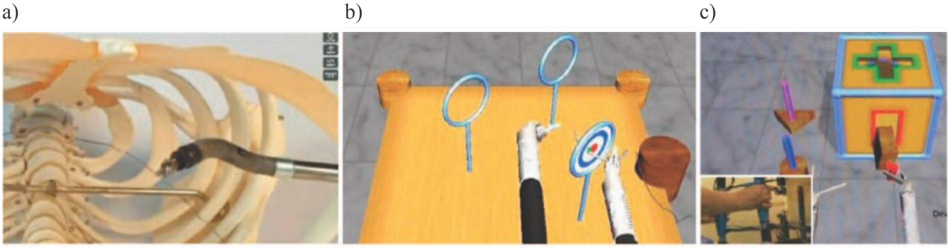


Fig. 18. a) Surgical tool b), c) Training system [44]

4. ROCH-1 – description of an own constructed new generation robot

In recent years, there are more and more attempts of improving the devices applied in minimally invasive surgeries, which results from the desire to carry out more precise procedures. This would limit any injuries of the patient and shorten the recovery period. The significant drawback of the emerging structures is the fact that the applied surgical tools are not to be used multiple times. This increases the costs for single procedures. Moreover, the majority of robotised tools available for surgeon-operators is characterised by a stiffness of the working terminal which, apart from turning the grips and ability of bending the final part, does not offer additional controlled movements, which limits the amount of possible manoeuvres.

In the presented structure of a multi-element surgical manipulator of the new generation, particular attention was paid to eliminate the aforementioned failures, providing a flexible configuration of tools, high precision of motion, as well as provide tight, replaceable antiseptic covers that are disposable after each use.

4.1. History of ROCH-1 and design assumptions

The design of the ROCH-1 surgical manipulator emerged as a result of a joint cooperation of employees across three units: the Department of Automatics and Computer Science at the University of Technology in Rzeszów, the Section of Mechatronics, Automatics and Optoelectronics IT of the University of Rzeszów as well as the Department of Robotics and Mechatronics of AGH in Cracow. The following structure was designed within the framework of the grant obtained from the Ministry of Science and Higher Education 2376/B/T02/2010/38 with its first patented version no. P-391263.

The inspiration to create a surgical manipulator originated from the doctoral work of F. Cempolin [2] of 2005 in which he tackled the problems of manipulators applied in minimally invasive operations. There had also been significant discussions throughout Polish medical circles for many years. They concluded that the solutions have several drawbacks, among which, apart from high prices of commercially sold robotised medical systems, are the low flexibility of working tools as well as single- or several-use tools.

The design and construction of a prototype system for performing surgical operations with the use of a manipulator with an innovative structure, which allows eliminating observable failures, requires creativity, knowledge, experience as well as gaining proper funds for financing the prototype. The team leader was Ryszard Leniowski (University of Technology in Rzeszów) who, upon the support of other members, obtained a grant from the Ministry of Science and Higher Education for implementing the undertaking in 2010.

It was assumed that a new construction should create a multi-part open cinematic chain, have a cross-section which does not exceed 10 mm and consists of readymade elements. Other design assumptions were:

- own mechanical interface among the elements,
- relatively easy installation, reached at the level of micromechanics,
- built-in BLDC drives along with transmissions,
- sensors integrated with the construction,
- ability for multiple use,
- ability for sterilising the manipulator.

Within the framework of the research project, the first version created of the ROCH-1 manipulator included both the mechanical part i.e. a module structure of the microprocessor system to control the drives, as well as the extended software based on modern algorithms of processing images and 3D positioning [5]. As a result of the hard work by the team, the mechanical structure of the manipulator evolved - there were many virtual models, on the basis of which, particular variants of the designed solutions were analysed. At this stage, many technological improvements were brought about by the builders from the Tooling Department of WSK PZL Rzeszów. Due to the miniature sizes of the device (with a diameter below 10 mm), it was impractical to design unique microtools in order to perform and mount the prototype. Many problems were also on the side of firms which are the only suppliers in the world regarding: microdrives, controllers or microscrews, which delayed the non-profitable, unit orders. The prototype of the device is as follows.

4.2. Description of the ROCH-1 modules

The ROCH-1 manipulator, assigned for supporting minimally invasive surgeries, is composed of six modules, with differentiated lengths of diameters ca. 10 mm, and is connected with joints. Particular elements are equipped with a mechanical interface, providing modularity of the structure and are equipped with their own drive. Such a solution gives an opportunity of easy reconfiguration of the device and adjusting it to several operations as well as location of the operating field inside the patient's body (opportunity to include parts of the extended arms). As drives of joints, BLDC motors were applied with a diameter of 3 mm, along with Piezo motors to move the grip. In order to diminish the risk of infecting the patient, the robot was covered with a replaceable, tight and flexible antiseptic coating (apart from the effector which is a single use device). Thanks to separation of the mechanical system from the human body, it is possible to use the device for multiple purposes.

Fig. 19. Exemplary configuration of the manipulator, particular elements were marked with numbers

The present concept is currently being developed further using other solutions. The complete set of modules is provided in fig. 19. The first of them, 1DOF with a length of 55 mm (fig. 20a) has one degree of freedom with a the turning motion. It is equipped with the greatest, among the applied non-brush structures, of DC motors connected with a planetary transmission that is connected to the base (fig. 19, 1). The main application of this device is to lift other elements. Moreover, its length was designed in a manner that would allow it to go through the trocar to the inside of the patient's body. Another module is the 1DOFkr (fig. 20c), with a length of 25.7 mm. This element also has one degree of freedom, but it relies more on an angular motion. Along with the previous module, it is coupled with a second arm, which allows it to manoeuver in a way to omit selected organs as well as reach difficult to access areas inside the patient's body. It should be emphasised that this feature is extremely important as it decreases injuries during the procedure and shortens the recovery time. In case of more difficult operations, with a more complicated path of access to the operating field, the selection of configuration may be changed, e.g. using two 1DOFkr elements. In this manner, there is flexibility which in contemporary solutions is regarded exclusively as the terminal of surgical tools itself.

Another module, 1DOFr (fig. 20d) provides a similar range of motions as the previous ones. This element has a length of 24.5 mm and allows significant increase of working space of the manipulator, especially in case of having both arms equipped with this element. Another, more constructively advanced module is the 2DOF (fig. 20e) with a length of 23.6 mm, which has two degrees of freedom and four Piezo motors inside. Moreover, inside each element there are 4 integrated ASIC controllers, communicating by an I2C interface with an external controller. The 2DOF module imitates the role of a wrist, with a motion that ranges from –22° - 22°, horizontally and vertically. The 2DOF element may be used exclusively as the module preceding the surgical tool.

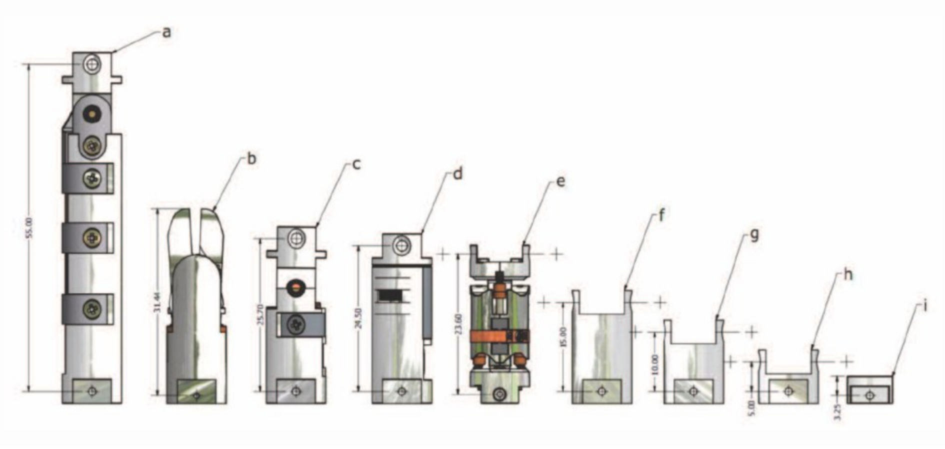


Fig. 20. The combination of the arms of the surgical manipulator along with empty elements and given lengths; a) 1DOFdł, b) 1DOFch – grip c) 1DOFkr, d) 1DOFr, e) 2DOF, f, g, h) Empty elements with the lengths: 15, 10 and 5 mm, i) Joint for elements with a different standard of connections

The most significant element of the manipulator, from the viewpoint of the procedure, is a working tool (grip) with various shapes and functionalities, starting with holding tissues, by clipping, incising as well as stitching postoperative wounds. Presently, the structure of the grip has many limitations. One of them is proper location of motors, strong enough to perform operations freely. In the presented exemplary solution, it was decided to apply two BLDC motors with diameter of 3 mm, which along with the screw transmission, drives the mechanism of levers moving the jaws of the grip. This solution gives a possibility of gaining maximum strength to 16N. Concurrently, there have been intensive works held on improving the structure so as to gain better forces and greater scale of integration.

Apart from the modules including motors, there also have been designed elements extending arms, in the form of empty elements. Their application expands the configuration of the manipulator allowing it to gain extra working space. These elements are made of aluminium alloy and are connected by 1.6 M screws with other modules (Fig. 20f, g, h). On the inside there are two canals to lead signal wires and motor controllers.

All connections between modules are unified, except for the 2DOF element. This element, due to its complicated internal structure allowing symmetry, requires an additional connection which allows it to connect the 1DOFr with 2DOF [4].

4.3. Motor, measurement and cabling systems

Motors of joints are implemented mainly with the use of BLDC motors manufactured by FaulHaber [15]. The producer has motors with diameters of 1.9 mm and along with them, it offers a vast selection of planetary transmissions and linear mechanisms. The biggest motor, type 0620C, has a diameter of 6 mm and a built-in encoder. It also disposes a maximum torque of 0.36 Nm. However, their smaller motor, type 0308A, has a diameter of 3 mm with an encoder that is connected separately. Along with the amplifier, which is also available offered by the company, has a designed structure that allows for 52% efficiency.

Another motor applied in the structure of the manipulator is an innovative linear actuator, using the effect of Piezo electricity and ultrasonic vibrations. This motor, with a height of 3 mm and length of 6 mm, is offered by Squiggle [16] and has a maximum force of 0.55 N. The actuator may move linearly, which is accompanied with an unfavourable turning movement. This problem was solved by applying a proper structure of pushers and *ball and socket joints*.

The advanced structure of the robot makes it difficult to pass power cables.

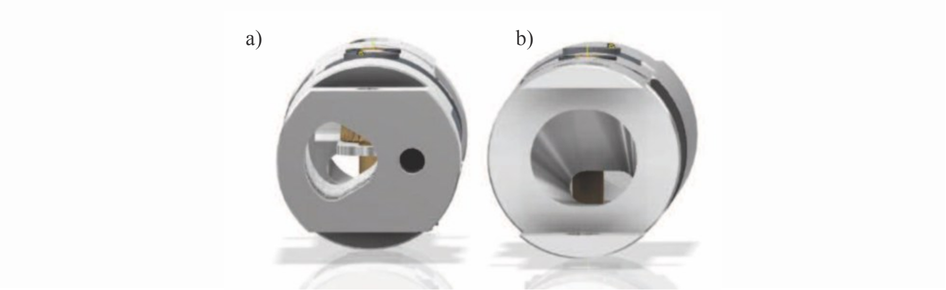


Fig. 21. Outlet for the 1DOFkr element
a) Cable duct in the corpus, b) Joint with the cable duct

The whole manipulator consists of five BLDC motors, five piezoelectric actuators and two encoders. Each of these elements must have a power signal and there should be a proper division of signals so as to limit electromagnetic interactions, which may disable the measurement of position and work of the I2C interface. Another limitation is a very small space to run the cables, however, the greatest problem is located in the joints, which are movable and include additional elements - transmissions - that limits the available space. In figure 21, there is a view of the corpus with the cut outlet to pass cables for the 1DOFkr element.

An indispensable complement of the mechanical structure of the manipulator is the control system [7]. It generates an optimal trajectory of motion, designed on the basis of the mathematical model of the device [6] as well as information on working space (operating field inside the patient's body). It allows performing many additional tasks, improving procedure functions connected e.g. with scaling the motions of the tool in comparison to real motions of the surgeon-operator, improvement of manoeuvre precision, elimination of vibration, and many others. The presented manipulator has been developed with regard to construction assumptions allowing work of the device inside the patient's body.

5. Conclusion

It is not difficult to notice intensive works and significant funds spent on the development of medical mechatronic systems. Within the last 10 years, the thinking of physicians and patients has been radically changed concerning the means and possibilities of operating treatment, mainly thanks to greater and greater access to minimally invasive operations. Currently, there is a range of robotised surgical systems, which during procedures may help surgeons in their work. It also helps shorten postoperative wounds and recovery time. The Da Vinci robot is a widely known and highly advanced robotised surgical system. However, despite the fact that the number of operations performed with the assistance of this robot is great, there is only one hospital where such operations may be performed in Poland due to the high costs of the system along with a single procedure.

The own structure of the surgical manipulator may be an alternative and much cheaper solution, allowing - after proper configuration - performance of various minimally invasive procedures. In order to implement such a structure, a standard of combining several modules was developed, which properly combined, provided full functionality and flexibility of an arm, as well as possibilities of accessing difficult to reach operating areas inside the patient’s body. It should be emphasised that the proposed device consists of the elements produced in a series, but due to miniature sizes, part of the details must be performed upon orders. Despite difficulties at the preliminary phase of developing the prototype, the presented model of a manipulator is relatively easy in mounting as well as technologically feasible. Obviously, due to the weight and specificity of applications, the implementation of the devices into hospital practice should be preceded with several laboratory and clinical research studies, during which it will be discovered how it satisfies the expectations of surgeons and patients.

Summary

This article presents the review of robotised mechatronic systems applied in medicine. Due to a dynamic development of this field, an own classification of such systems with particular emphasis of robots used in minimally invasive surgeries (MIS) was implemented. The particular classes have been characterised and their representatives been described. Much more space was devoted to “medical robots”, due to the contribution of authors in their development. Apart from presenting the most known MIS robots, their typical parameters, capabilities, and limitations, this article also defined a prototype of an own structure, the ROCH-1 surgical manipulator.

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Mechatronic design of gripping for a humanoid robot

Krzysztof Mianowski*

Summary

Mechanical design and a prototype of the gripper – an artificial hand for a humanoid robot, are presented in this paper. It has been described as a methodology of mechatronic design, which allows highly integrating mechanical/electric/electronic parts of the prototype. It has been shown that it is possible to create basic functional characteristics of the solution in the virtual design phase.

The gripper was designed for different tasks, those typical for natural human hands, and additionally for expressing robot/human emotions.

Keywords: artificial hand, humanoid robot, artificial manipulation.

1. Introduction

Throughout recent years, during the development of new robot systems, there has been constant development and interest in service robots and personal robot assistants. More and more scientists worldwide are becoming interested in the possibility of controlling processes by robots, which in the past was only possible for a human and his hands. The emerging humanoid robots need new means of communication, in particular, with reference to the methods of manipulation as well as to the manners of acquiring information about the surrounding environment and mostly expressing emotions, including non-verbal ones. Regardless of this fact, there are new solutions sought, in which a robot, its manipulator and in particular the gripper (hand, palm) has to satisfy new, mostly sophisticated conditions, during which the same gripper has to provide a possibility of servicing various processes of manipulation by implementing various gripping motions. In such solutions, grippers are equipped with various sensory devices, allowing implementation of various interactions, increasing safety of the manipulated object, robot and its environment.

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It should be emphasised that the effective introduction of robots to the human environment in everyday life significantly depends on the development of such robot systems which would provide reliability, safety and simplicity in a complex way. It is planned that in the nearest future, robots will help humans in work and everyday life by:

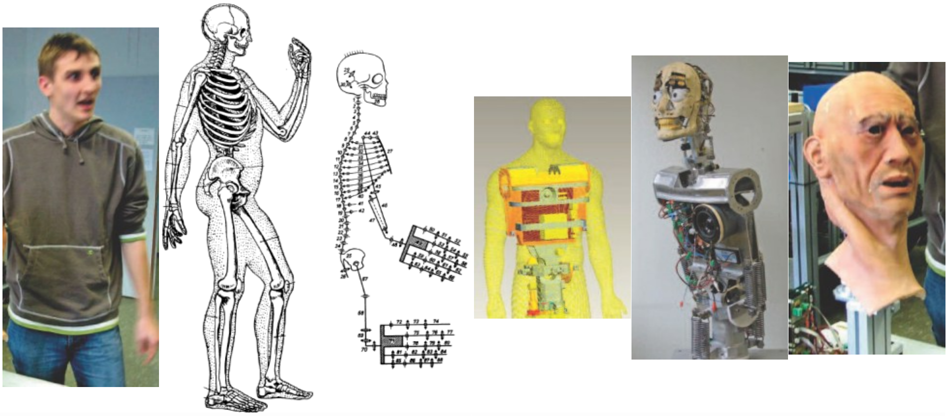
- replacing humans at work - e.g. by individual work of the robot replacing a human (majority of industrial robots),
- Cooperation with a human - e.g. by coordinated actions of following activities of a human,
- assistance in performing work requiring support - e.g. holding a lamp lighting the work area or operating a camera,
- telemanipulation i.e. “extending hands of a human” also at a distance as a device for e.g. performing surgical operations via the Internet.

This requires seeking/development of new concepts of design paradigms allowing complex regards towards a robot within a design as well as various requirements and conditions concerning the actions performed by a robot and problems which are typical for humans. Such paradigms rely on mechatronic designing in a complex manner combined with concepts of solutions e.g. connected with nature with regard to modern solutions for mechanic, drive, cam, differential systems as well as sensory ones, and in particular control systems and control algorithms, combined together with a manner providing high level of integration and rational interconnections of composite elements. Interconnection is understood as not only strict geometrical connection within the space, but also a possible comprehensive interconnection and completing the functions and tasks both in the scope of a mechanic system as well as sensory tasks and control functions, mostly repeatedly increasing possibilities and functions of combination networks (connections) within a system. Internal relations are formed within a system located at a lower and medium hierarchy of importance or generalities of performed tasks and processes, allowing rationalisation and optimisation of labour manners of the system, increasing safety and reliability as well as easing the schemes (conceptions) of internal connections. In other words they improve their simplicity of use. Works on development of gripping capabilities of robot arms are developed both in the scope of new solutions of mechanic systems e.g. resembling a human arm [6, 12] as well as seeking so called optimal grippers and using sensory information e.g. force sensors: wrist, joints, surface, approach sensors, miniature cameras built in the gripper’s corpus etc. [7, 12].

2. Methodology of designing

The general course of action while designing and constructing a robot resembling natural objects may by easily explained on the basis of the ROMAN robot (RObot huMan interAction machiNe) [2] developed and built in recent years at the University of Technology in Kaiserslautern (Germany). This scheme has been illustrated in fig. 1.

Resembling the original - live organism (natural object) treated as a biological model (fig. 1a) as well as its similar description in the form of e.g. scheme of the anatomic atlas treated as the set of basic composition elements (functional) (fig. 1b) for the analysis of motoric functions. This may be used as a method of modelling, relying on creating a cinematic scheme pursuant to the procedure of schematisation of cinematic sets with the use of graphical symbols of parts and cinematic pairs. This scheme may be presented in this manner so as it will resemble a similar shape of the original (fig. 1c). This manner of graphical presentation allows identification of the affiliation of the scheme to the original. During the analysis it helps in the interpretation of partial results regarding particular functional fragments which improves the understanding of actions of the natural object treated as the biomechanism and constitutes the starting point for the humanoid robot. After the division of the cinematic scheme into fragments equivalent to basic organs (hand, leg, spine) the equivalent schemes are analysed in order to perform indispensable simplifications. Then there are designed mechanisms with simplified cinematic schemes (original models) with the properties equivalent to the functional assumptions within the robot design. These mechanisms form parts with proper shapes and are equipped with bearings, drive with cams, drive differential systems, built-in sensors, as well as power and control systems. They were designed using 3D CAD methods as an integrated mechatronic structure with high preliminary functional and aesthetic properties. The design - 3D model of ROMAN mechanisms developed in the ProEngineer system is shown in fig. 1d. It has been performed on the basis of the design of the robot's fragment in figure 1e. The corpus of the robot is mounted to the base on the spherical mechanism where there are three degrees of freedom to manoeuvre the lumbar spine - turn regarding



a) Original – biological model

b) Scheme of the anatomic atlas - set of functional elements

c) Cinematic scheme

d) Design – 3D model

e) Fragment of the robot prototype

f) Silicon mask imitating the face of ROMAN

Fig. 1. Use of the biological model in the structure of the humanoid robot

the vertical axis, forward and backward bending, left/right side bending. In order to compensate the influence of the gravitation force on the drive systems, proper spring loads were added, which is visible in the photograph. In the metal sheet structure of the corpus, the motherboard of the control computer, stabilised voltage power system, and drive control were installed. The head is mounted on the corpus with the use of a mechanism similar to the one applied in the lumbar spine, however in its base, there is one additional turning degree of freedom, so as to visually and more naturally perform movements of bending the head forward and backward. The head of the robot is covered with artificial skin in the form of a mask made of flexible silicon - fig. 1f. On an additional note, it is worth adding that in the technological process of constructing the face mask, properly prepared threads made of plastic – eyebrows, are located in such a manner that they imitate a natural look and were included in the mask in a similar manner as natural hair nested in the human skin. The mask is mounted to the elements of the skull and mandibles as well as additionally movable slides on the surface of the skull, so called fasteners, in a way so that during movements of the head, the skin moves imitating changes in the face, reliably imitating the expression of emotions. This developed solution constitutes the model of a humanoid robot allowing highly repetition of interactive studies on behaviours of robot-human contacts in the scope of expressing emotions. For this purpose, robot control algorithms are communicated with artificial intelligence programmes.

3. Gripper solution of an artificial hand

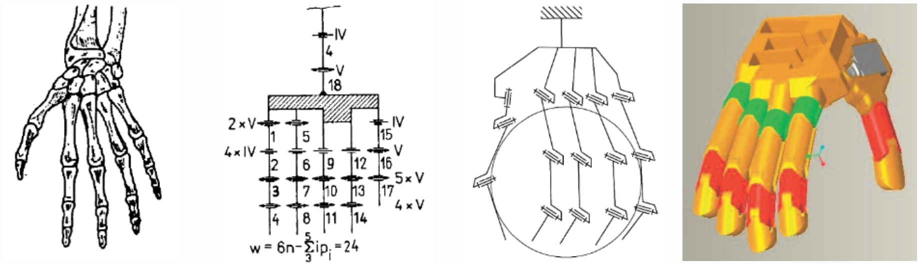
In order to perform manipulation tasks for a manipulator-robot, a gripper plays a significant role. Its task is to grip an object, to properly hold that object during transport and to perform other manipulation tasks, as well as release it at a target point. The majority of grippers of industrial robots mostly have a simple structure with one degree of freedom. They are equipped with a drive mechanism built in the corpus along with a clamp like structure that allows it to take hold of an object [8, 9]. The size of the jaw opening and grip force are properly selected to fit the dimensions of a certain object, its weight, material, conditions of the object surface etc. The grippers applied in industrial processes are specialized grippers and are assigned for servicing one type of manipulating task, mainly within the framework of a given process or group of processes.

At the current phase of design, new solutions for the gripper are being developed with a type of artificial hand. This is assigned for support in expressing emotions as well as for intelligent manipulation using sensors. Considering the factual condition of drive systems, control and sensory available on the market, as well as the present condition of the laboratory base of the Robot Study at the Technology University of Kaiserslautern in the scope of production technology (fast mechanic prototyping) and control, it has been concluded that it is possible to develop an advanced gripper - artificial hand, reliably reconstructing the shape and functions of a human’s hand along with drives, sensory systems (e.g. artificial skin for measuring the distribution of surface pressure) and control systems built into hand. Moreover, it has been assumed that for controlling a hand, there should be a new principle of control. It should rely on the analysis of sensory information from the gripper, robot and its environment in order to work out a better strategy to grip e.g. delicate objects with complicated shapes, but also anything within the robot's reach. During the development of the new grippers, certain assumptions should be made regarding the shape of the objects, their sizes, mass, hardness and susceptibility of external surfaces, resistance (resistance of being crushed by the forces caused by the grip), state of surface, different possibilities of gripping etc. These assumptions are equal to the possibilities of a live working hand, but it requires extended analyses concerning the technical possibilities of performing equivalent modelling tasks with the necessity of using inanimate technical matter. Pursuant to the formulated assumptions, the problems regarding technology was thoroughly analysed i.e. possibilities of solving a cinematic system, drive, location of sensors, supply of power and control systems in the most integrated and compact manner so as to provide high functional properties of the gripper. Another factor which should be included was a desire to create a solution, with the use of which it is possible to grip objects. For example a robot with a gripper which could solve a problem in a "mechanical and intuitive manner". This concerns such objects as a stiff glass bottle, soft plastic bottle filled up with liquid of changeable content, stiff plates and cubes, golf balls, tennis or ping pong ball or an egg etc. As a result, in the construction solution as well as in control, certain attention should be paid to additional undetermined factors influencing the process of gripping/manipulation as well as objects which a robot with a gripper would have to effectively manipulate.

Moreover, the designed artificial hand of the robot has to be used for presenting the conditions equivalent to expressing emotions, similar to the emotions of the original i.e. a human being. In this situation, in a natural manner it was assumed that the given cinematic scheme of the mechanism will be reliably similar to a human hand, number of fingers was assumed as five. The sizes of a palm and particular fingers were individualised and pursuant to the anatomical atlas and biomechanical tables. It was possible to adjust the size of the hand within the range of a 95 percentile human hand.

Developing the design of the gripper was preceded by the analysis of the knowledge state as well as study works on real properties of the original - a human palm. On the basis of the anatomical atlas and available literature [9] the number of bones and motoric joints - fig. 2a, and the exemplary cinematic schemes developed by other researchers fig. 2b, were analysed. Significant simplifications were made as their started to become a great number of parts, cinematic pairs as well as drives. It therefore has been assumed - fig. 2c, that four fingers i.e. the index finger, middle finger, ring finger and the small finger, will have three degrees of freedom in the form of bending motions. The thumb will also have three degrees of freedom, however, the first one will be developed as a motion that moves parallel to the axis of the palm. The other two degrees of freedom will be developed similarly to the other fingers i.e. as bending motions.

This simplification of the cinematic scheme of the entire palm provides a possibility of a reliable reconstruction of the internal geometry of a palm as well as it allows rationalisation (minimisation) of the number of drives that are necessary for the proper fuction of the gripper.



a) Skeleton of a human being's palm

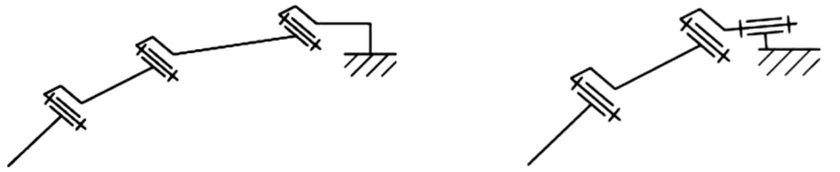
b) Cinematic scheme of the palm

c) Simplified scheme of the gripper

d) 3D model of an artificual palm

Fig. 2. Assumed simplifications and 3D model of the artificial palm

Pursuant to the scheme as in figure 2c, a 3 D model of a hand was developed and is presented in fig. 2d. In figure 3a, the basic cinematic scheme was presented for fingers with three phalanges i.e. an index, middle, ring and small fingers. We have a mechanism consisting of three phalanges connected with each other by means of turning joints in the flat open cinematic chain. In the figure 3b, the basic cinematic scheme was presented for the thumb. It was assumed as a fragment of a mechanism from figure 3a but with two phalanges, however, it was also provided with a turning point to move parallel to the palm axis.

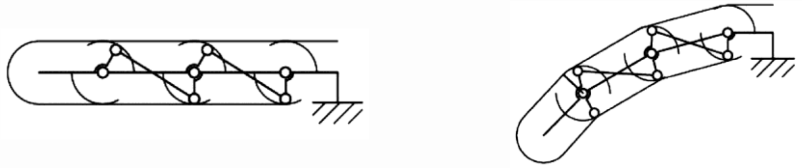


a) Index, middle, ring and small fingers

b) Thumb

Fig. 3. Basic cinematic schemes of fingers

Presently, it was assumed that drive systems in the form of typical cheap commercial modelling servo-units would be built directly into the palm, however, the transmission of motions would be performed with the use of flexible lines. After preliminary research, it turned out that the use of these lines requires preliminary stretch and control, along with feedback from the force. This complicated the solution and significantly increased costs. In this situation, the structure of the finger mechanism, a cinematic feedback of further phalanges was applied with the use of a joint quadrangle mechanism, a so called cross joint. In figure 4a, a cinematic scheme of a finger from figure 3a is presented, but with the use of symbols applied while schematisation of flat mechanisms. The basic mechanism was extended by additional "supports" connected with basic elements (similar to hypomochlins and retinaculum in the bone system of live organisms) which, within the elements were combined by creating joints. This was coupled along with the basic elements successively linking mechanisms using a four-bar cross joint.

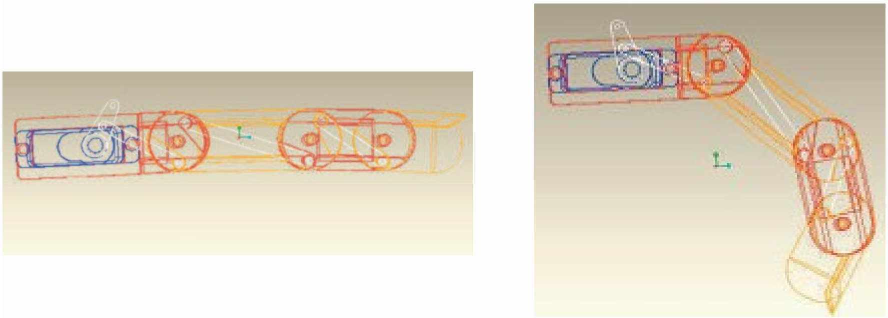


a) Scheme of a finger with phalanges connected cinematically

b) Scheme of the finger mechanism in the bent position

Fig. 4. Principle of the linked finger mechanism

This linked finger mechanism has one degree of freedom towards the base. The drive is transmitted into the finger from the motor crank located in the palm. The first element is moved through a crank using a single joint, however further phalanges, due to the aforementioned cinematic linkage, bend at sequential joints in such a manner that the successive one moves towards the previous one and assumes an angle equal to the angle of the first bend towards the palm. In figure 5, there are 3D project prints of a single finger shown in "wireframe" and "shaded" scales designed as a mechanism.



a) Finger in a straightened state – "wireframe"

b) Finger in a maximally bent state – "wireframe"

a) Finger in a straightened state – "shaded"

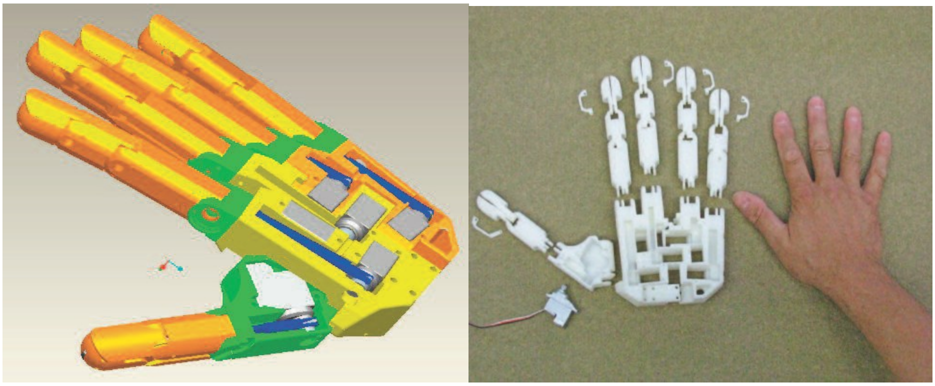
b) Finger in a maximally bent state – "shaded"

Fig. 5. Design of the linked finger mechanism

4. Functional project with the use of modern technologies

The developed model was made from ABS material using the fast prototyping method on the Dimension machine. It was used in preliminary research as well as a precise statement of assumptions and rationalisation (optimisation) of the target solution. It should be emphasised that the application of the new technology of fast prototyping elements using spatial printing allowed regarding completely new conditions within the project such as the shape of details, manner of their interconnection and penetration within the space, as well as the general management of the usable space of the mechanic structure.

In order to minimise the resistance of motions and provide high precision of positioning and measurements of forces/torques, mostly in the construction of the fingers and joints, miniature rolling bearings were applied. To fit these bearings, there were mounting sockets designed, allowing integration of bearings with the bearing structure. In the joints, a structure of interconnected layers were applied to allow "passing" upper and lower joints connected by means of various elements. In order to measure the force of the gripper in the last phalanx of each finger, there was a built-in two-state sensor, generating a signal of the connection with the object, to which a two element part was precisely adjusted. The outer layer was covered with construction plastic. This precise manner of adjustment turns out to be possible only by using this method. In the structure of the palm, a precise adjustment of sockets for engines, sensors, electronic systems as well as power packs and electric stabilisers were designed. Figure 6a presents a virtual prototype of the developed structure of an artificial hand. On the basis of the designed parts, 3D prints and all bearing elements of the hand were created as seen in fig. 6b.



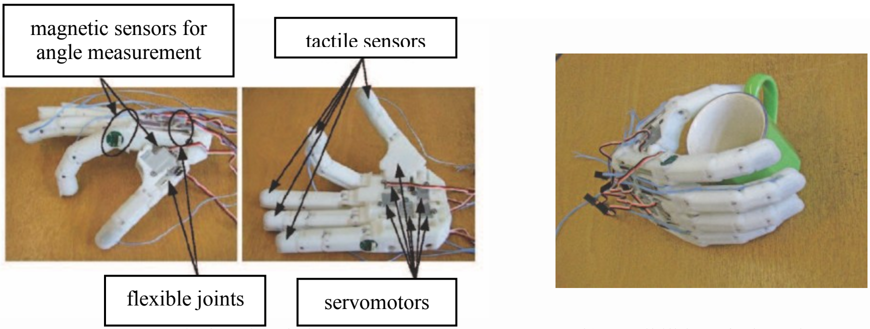
a) Design of a hand developed in the ProEngineer system as a mechanism

b) Basic elements of a hand printed using the 3D method - dimensions similar to natural

Fig. 6. Virtual model - prototype of a mechatronic hand of the humanoid ROMAN robot

5. Prototype of basic functional properties

Primarily, a mechanism including stiff elements was developed, however, due to the kind of drives, the control functions became problematic.



a) Basic functional elements

b) Possibilities of adaptation to the object

Fig. 7. The prototype performed by 3D printing of a mechatronic hand of the humanoid ROMAN robot

As a result, the construction of the connection transmitting the drive from the servo-drive onto the first phalanx included a flexible element - a two-way spiral spring. It allowed flexing the mechanism of each finger and, at the same time, direct measurement of the force. In order to do that, at the mount of the finger, an additional angle measurement sensor was installed. In figure 7a, a distribution of servomotors, flexible joints, tactile sensors and magnetic sensors for measuring angles are presented. Figure 7 illustrates the preliminary researched gripping possibilities of an artificial hand. It will be additionally covered with a flexible coating made from silicone rubber, so called artificial rubber, including microelectronic tactile sensors for measuring semi surface forces on contact with the manipulated object.

Conclusion

Preliminary research presented high functional, usable and aesthetic values of the designed artificial hand/palm. Application of the flexible joints increases the adaptive possibilities and extends the scope of possible tasks as well as potentially performed processes. Currently, the gripper is mounted on the arm/hand - manipulator of the humanoid robot and is undergoing intensive usable research.

Summary

This article presents a project and prototype of a gripper type artificial hand/palm, assigned for a humanoid robot. A methodology was also described of mechatronic

designing allowing high integration of mechanical composite electric and electronic elements, as well as shaping basic functional characteristics of the product at the design stage. The task of the gripper is servicing typical manipulating tasks which are performed by a robot, reliably imitating a human, in particular supporting expression of emotions by a humanoid robot.

The work was performed within the framework of the design of the humanoid ROMAN robot supervised by prof. K. Berns at the Technological University in Kaiserslautern – Germany.

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Elements of supervision and control over a wheelchair for persons with a high level of disability

Ryszard Leniowski*, Marek Czujko*

Summary

This paper presents an original concept of trajectory planning for a 'smart' wheelchair, designed for people with a very high degree of disability. The project involves the construction of a vehicle, coupled with a complex computer system that provides high autonomy movement (defined traffic routes and sectors). The route is generated on the basis of city-plans in the form of bitmaps with GPS markers, and the motion path using the cubic polynomial splines for the representation of the Catmull-Rom. The advantage of this method is the automatic determination of speed at control points. The resulting profiles are saved to the database associated with the patient and his vehicle. The developed task is a component of a wheelchair surveillance system, which is a complex mechatronic system.

Keywords: wheelchair, trajectory planning, control and surveillance systems, Mobile robots.

1. Introduction

For the last two years, at the Department of IT and Automatics from the Rzeszów University of Technology, under supervision of R. Leniowski, there are performed research, design and construction works aimed at developing a smart wheelchair for persons with a high level of disability. This wheelchair is being designed with satisfaction for people providing round the clock care for patients with a high level of disability. The project assumes creating a kind of a mobile robot, linked with an IT system which will allow great autonomy of work, provide caring functions (with the option of diagnostics of medical conditions of the patient on-line) and will engage the patient in an intelligent manner. It is about the situation in which the robot-wheelchair-assistant will take some burden from the carer for several hours and give him an opportunity to perform necessary organisational tasks at home. It has been assumed that an intelligent wheelchair is to be used in cities and villages, which means that it will be

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possible to avoid dangerous situations within road traffic, overcoming barriers, both planned (stairs, high kerbs, lamp posts) as well as unplanned (stone or potholes in local rural roads).

The implementation of the project is connected with solving many tasks with a scientific and technical character, which means that its significant components are connected to the field of mechatronics. A wheelchair for persons with a high level of disability is a great example of a mechatronic device with extended “intelligence” allowing mobility in collision areas. Decisive algorithms use the flow of information incoming from the extended sensory system, monitoring the condition of the wheelchair and the patient. The implementation of developed decisions comes to the control over the wheelchair, the regulation of the armchair as well as periodical notification to supervisory employees about its state. Built-in motion control systems are very complex mechatronic systems which include drive modules along with transmissions, power controllers and digital regulators functioning as local servomechanisms coordinated by a master control.

Up to this moment, there have been preliminary projects conducted of a wheelchair with an independent electrical four wheel drive (first project). Moreover, the second project assumes adding an additional two-partial rubber caterpillar which would allow overcoming more difficult barriers in a rural area as well as high and winding stairs.

The work presents two implemented partial notions performed within the framework of the project. The first notion concerns planning the motion trajectory in a city on the basis of processed city plans, and more specifically: in a selected district, in which the patient lives. The wheelchair may move only on marked routes or defined sectors. The marked routes must regard the parameters of pavements (width, arc radius), crossings and barriers (lamps, road signs etc.) The motion sectors are city green areas (parks) or communication space for huge buildings (corridors) with limitations in form of trees, bushes, flowers or pillars. This is all done by saved detailed data defining routes and sectors from a database of the trajectory for accessing significant health care centres and areas of safe recreation [1].

The second notion described in the work is the system of automatic generation of trajectory, based on cubic curves, formed in the representation of Catmull-Rom. Thanks to this representation, the significant parameter of the wheelchair, which is speed, is automatically calculated on the basis of positions of hub points.

These are original, author’s solutions which represent mechatronic attitude to designing, characterised by integration of the devices, algorithmic and software. Solving partial solutions, the economic aspect was considered. The software was produced with the use of recognised standards e.g. free library of BOOST (software technologies, network layer), Qt (user’s interfaces) and libraries OpenGL (graphical interfaces, motion animations).

2. Existing device solutions

An ‘intelligent’ wheelchair is a device which gives mobility to persons with various levels of disabilities. It helps those who have complete motoric dysfunctions, arising from various kind of disabilities from birth or acquired e.g. being the result of post-accident complications. It helps patients and carers to improve their quality of life. Obviously, the wheelchair has to meet a range of standards and certain functions. The functions are one of the most significant criteria according to which, wheelchairs are divided. These works [3], [4] provide much information in this capacity. Apart from functionality, the wheelchair should be characterised with comfort and durability, providing ease in motion, and must be aesthetically manufactured (nice).

The work discusses the wheelchair with electrical drive. First information on electrically driven wheelchairs emerged at the beginning of the 20th century. Probably, the very first electric wheelchair was constructed in 1912 by George Westinghouse who constructed an engine with a power of 1.75KM to a three-wheeled wheelchair. The device had a prototype character. Mass production of electric wheelchairs was started in 1956 by *Everest & Jennings.*

Contemporary wheelchairs with electric drive are advanced mechatronic devices, including complicated control and communication systems. Wheelchairs are produced on the basis of certain standards, however, classical solutions assume an armchair based device. Electric wheelchairs may move inside buildings (hospitals, daily health care centres, sanatoria etc.) or outside, overcoming typical urban barriers (kerbs, bumps on pavements, stairs etc.) Width is a very important parameter. It must be less than 90 cm so as the wheelchair could freely pass through doors. Indirectly, dimensions of a wheelchair are connected with a notion of manoeuvrability, measured by a turning radius. Manoeuvrability depends on the construction and drive transmission. Depending on the fact which axis is driven, wheelchairs are divided into: rear drive, front drive, central axis drive and 4 wheel drive (4x4). Figure 1 presents the aforementioned kinds of drives in a symbolic way. The driving wheels are marked with black rectangles and the control wheels are grey.

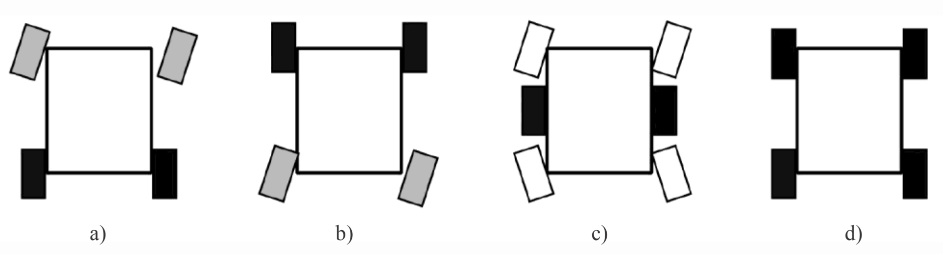

a) b) c) d)

Fig. 1. Drive of wheelchairs

Rear wheel drive (fig. 1a) is the most commonly met solution. The rear axis is located behind the centre of gravity of the wheelchair and this solution makes the device fast, however the turning radius is lower than with other solutions. A front wheel drive wheelchair (fig. 1b) is very manoeuvrable, but vulnerable to flipping over, thus the speed of such devices are lower than in comparison to rear wheel drive chairs. Central axis drive (fig.1c) provides the wheelchair with top manoeuvrability (e.g. turning around on point) and this is the best solution as the turning radius of the wheelchair is lower.

However, this system has a lower stability of motion at the starting and stopping stage, which limits its possibilities of moving outdoors. The fourth solution, four wheel drive, (fig. 1d) has the greatest features of the previously mentioned configurations and so called outdoor independence. However, this solution is more expensive than the previously mentioned and it additionally causes greater wear of tyres.

For the authors, the reference point is the *XENO* model manufactured by *OttoBock* [5], fig. 2, with a modern construction of a chair, allowing positioning of the patient.

Fig. 2. Example of a modern construction [5]

In this work, balance wheelchairs were omitted, which after some excitement, are losing their significance, due to high power consumption necessary for balancing the device.

3. Significant elements of a wheelchair with electric drive

Batteries - in modern wheelchairs, three kinds of batteries are used: acid batteries, gel batteries and new AGM batteries (*Absorption Glass Mat*). The cheapest are acid batteries, but due to the risk of electrolyte leakage, e.g. as a result of a collision, are most often replaced with gel batteries (the electrolyte includes sulphuric acid mixed with silica). These are safe and service-less batteries, however more expensive and heavier than acid batteries. The main competition for gel batteries are AGM batteries. This is an electrolyte battery with electrolyte absorbed in glass wool which fills the entire space inside the battery. Thanks to such a structure, the electrolyte leakage was eliminated even during mechanical damage to the battery. Currently, these are the best and most commonly available batteries for wheelchairs, though, the most expensive ones.

Engines - assigned for driving wheels and positioning the chair of the patient. Older structures used to have DC engines with ferromagnetic magnets. Nowadays, BLDC engines with neodymium magnets are more and more frequently used, with low power voltage: 12, 24 or 48 V. They are characterised by the greatest efficiency and power for capacity, which has a great significance in case of a battery powered wheelchair (set of batteries).

Transmissions – Transmitting the drive from the engine shaft may be made directly onto the wheels or indirectly, by means of various kinds of transmissions. If there is direct transmission of power from the engine, the engine shaft is connected with the wheel shaft. The feature of a direct drive (DD) is the immediate reaction of a wheel, which is an advantage. The direct drive requires application of slow-running and high-torque engines whose manufacturing has been implemented by only few companies in the world. The indirect drive uses transmissions to reduce the torque speed of the engine and increase the drive torque. There are applied toothed, worm, belt transmissions with a trapezoid or toothed belts. The transmission is also located in the chassis of the wheelchair and requires periodical maintenance. Sometimes, neglected transmissions are the source of troublesome noises.

Chair - Depending on the level of disability of a patient, the chair is individually selected. The height of the back, length of the seat, kind of thigh and side rests is settled along with additional elements such as a headrest or armrests. The chair is mostly equipped with seat belts which hold the patient in a stable position, protecting him against moving within the chair and against falling out. The selection of optimal dimensions of the chair is a difficult task, performed by specialist institutions. The width of the seat, depth as well as height of the seat and backrest are all taken into consideration. In many cases, there is some additional equipment which is to improve stability of the body due to the particular kind of the patient's sickness or disability. These additions include armrests, headrests and calf rests.

Material coating - An important feature of the chair is the material coating which must meet several rigorous hygienic standards (easy air permeability and absorbing humidity) and well as operating standards (anti-slippery, easy to clean). There is a range of solutions. The most interesting is e.g. *STABILO BASE* [6], fig. 3.

Fig. 3. *STABILO BASE* [6]

Fig. 4. VISCO foam [7]

This is a multilayer structure which may be freely formed so as to lighten sensitive parts of the body. Another interesting material is the memory foam VISCO, with a unique possibility of lightening pressure on the patient's body [7]. The foam fits to the body shape, fig. 4. Anti-bedsore action has VICAR pillows and mattresses, composed of hundreds of cells filled with air. The SELECT company has a similar solution, fig. 5. These cells have a very low friction coefficient which gives them a possibility of moving towards each other, causing a tight fit to the body.

Fig. 5. SELECT pillow [7]

Thanks to the dissemination of the technology of laser scanning, nowadays it is possible to design the shape of the seat to an individual structure of the patient's body. Scanning is performed at the patient's home, and the ready-made profile in a digital form (file) is sent by email to the producer. This method has replaced traditional techniques.

4. Concept of a wheelchair and design assumptions of the supervision system

It has been assumed that an intelligent wheelchair is to be used in cities and villages, which means that it will be able to:

- avoid dangerous situations e.g. traffic collisions,
- overcome barriers, both planned (stairs, high kerbs, lamp posts) as well as unplanned (stone or potholes in local rural roads),
- into public objects with no assistance (door with a standard width, e.g. 90 cm),
- get on low floor buses,
- manoeuvre a disabled person (lifting lower limbs, body positioning),
- conduct a dialogue with the supervision centre (condition of the patient and device).

The wheelchair has an electric four wheel drive (system in fig. 1d), with an optional caterpillar for climbing stairs. The drive includes 4 BLDC engines, mounted on wheel axis, digitally controlled with individual traffic controllers and superior computer. The batteries 2 x 12V, were used for power.

The design assumes a multilayer regulation of a divided chair of the patient (two part leg rest, back, armrests, headrest, security grips, side protectors) with the supports being filled with gel inserts. Estimates show that this wheelchair will be able to ride at a maximum speed of 12 kph, and with an operating time not less than 5 hours.

Auxiliary power was also designed (for the communication system) from the solar panel, playing the role of a parasol. The designed mass of the wheelchair does not exceed 150 kg.

From the viewpoint of the IT system, both the patient and the wheelchair may be considered in various categories, connected with functions and tasks, which have been assigned to them. As the supervision system is the soft Real Time application, this causes the applied software engineering to have two basic priorities. The first one is configurability of components; the second one is the aspect of time connections, expressed by the flow of actions and carefully selected architecture, allowing designing along with concurrency. Among the libraries available within the framework of GPL (general public licence) *Qt* is of much attention [8]. The applied technology of *Signal & Slots* allows easy connection of performed components. The perceived components, as a set of "programme blocks" generate *Signals*, which are connected to *Slots* of other components, forming complex systems. As the connections among components have a dynamic character, they may be disconnected/connected, and the system may assume various configurations. The stream of the data sent among components is then verified.

At the moment, there are three components developed:

1. Presentation component (graphical model of the wheelchair, graphical model of the rural area - vicnity of Boguchwala, graphical model of the urban area - Rzeszów, graphical model of measuring instruments);
2. Operator's interface component (map of movement area, sheet of the patient's condition (card file), sheet of the wheelchair condition, sheet of emergency conditions, sheet of remote control, sheet of statistics and prediction states);
3. Traffic planning component (map editor, module of servicing electronic city maps, module of automatic determination of the way to a pharmacy, health care centre, hospital, park, recreation areas).

Below, an element of the traffic planning component is presented - map editor.

5. Supervision system - map editor

The basic task performed by the supervision system of the wheelchair is map edition, representing routes and traffic sectors of the given area of a city or village. This task starts with loading a graphical file with a digital map, which should undergo constant updates. At present, the software supports *.jpg and *.png formats. The map may be downloaded from any portal type: *maps.google.pl, targeo.pl*. However, it must be converted to one of the aforementioned formats. Another requirement of the map is having a marking of the scale and coordinates, at least one control point along with marking the real GPS positioning of this point in space. Figure 6 shows fragments of the map along with a control point.

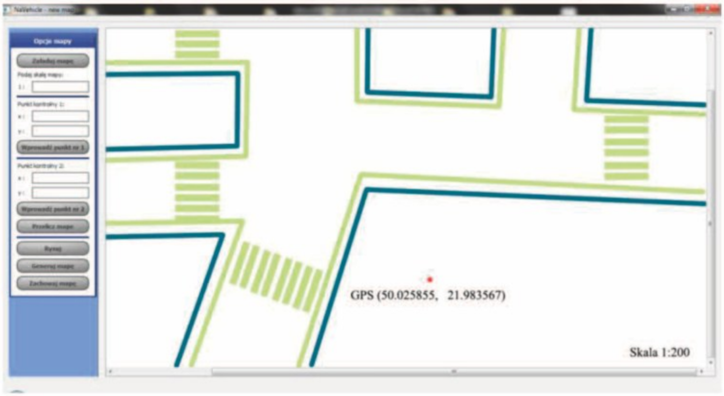


Fig. 6. The map editor window with an exemplary map

On the left, there is a dialogue field, used for determining the parameters of the functions processing graphical data. It is essential as the uploaded map is only a picture (graphical file), composed of pixels. Each pixel has its unique position *p(x, y),* which the real representation is defined due to the control point (with GPS) and scale coefficient. After performing these steps, there is the edition of routes and traffic sectors. Edition is based on determining routes in the form of curves after which the wheelchair may follow. The colour of the route is not incidental. This is a colour (0, 255, 0) of the RGB model and it defines maximum saturation of green without any red and blue colours. This colour is rare in nature, that is why it has been selected, fig. 7.

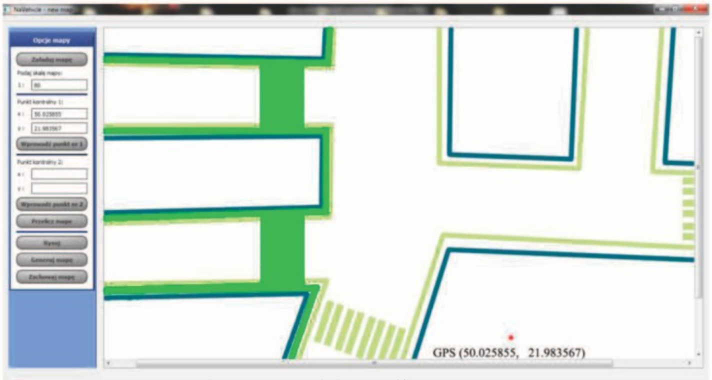
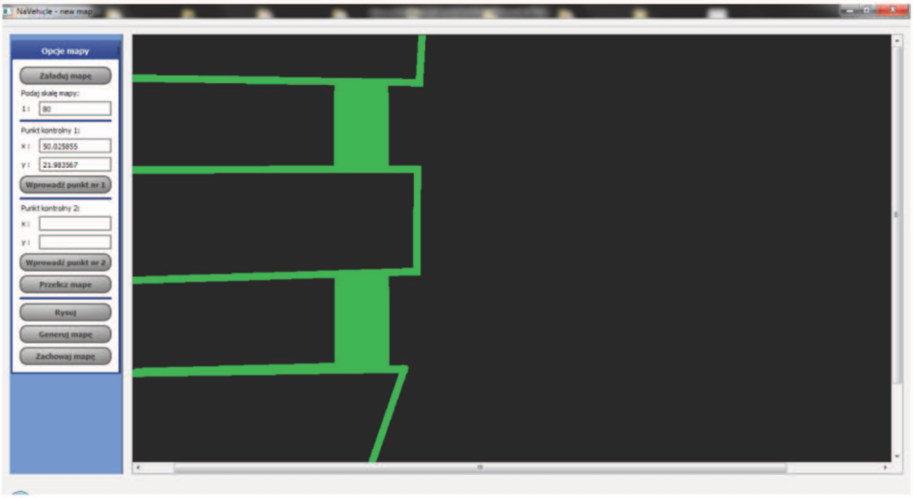

1: 80
x: 50.025855
y: 21.983567

Fig. 7. Determining traffic routes.

By marking a route in a colour which does not exist in the nature, it may be easily separated from the environment. Another step is removing it from the environment in order to obtain a two-colour picture, with black background and green routes, fig. 8. Such a picture is used for marking the routes of the wheelchair. After marking routes and generating maps, the data is saved to the database. Newly saved maps are assigned with a proper identifier and connection with a given patient.



Podaj skalę mapy:
1 : 80

Punkt kontrolny 1:
x : 50.025855
y : 21.983567

Fig. 8. Two-colour map

Routes visible in fig. 8, are treated as a connection of convex polygons, defined with vertices (x_i, y_i), fig. 9.

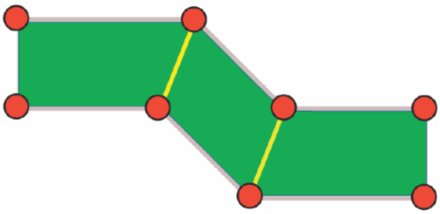


Fig. 9. Interpretation of the route traffic

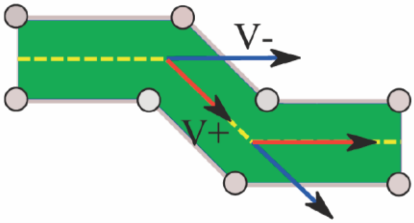


Fig. 10. Change of the speed vector when turning

Assuming that the traffic trajectory will be passing in the centre of the road, the route may be saved in the form of coordinate pairs:

$$\begin{cases}(x_i, y_i)_L \\ (x_i, y_i)_P\end{cases} \tag{1}$$

where L - means a point on the left of the route, though P - point on the right. The wheelchair must move onto the trajectory determined by the route (Fig. 10, broken line) with coordinates:

$$\begin{cases}x_i = (x_i^L + x_i^P)/2 \\ y_i = (y_i^L + y_i^P)/2\end{cases} \tag{2}$$

This is a trajectory in the form of curves, determined by control points (2). The problem is to determine the velocity vector in hub points, located at turning points, fig.10. Thus, a better solution is an application to planning a route, cubic integrated polynomials for representing *Catmull-Rom* [2]. This representation is featured with a very good matching to interpret control points of the obtained curve. Moreover, it has an built-in mechanism of generating velocity vectors at these points. Pursuant to the description *Catmull-Rom,* a cubic curve passes through all control points. The direction of the curve (tangent) at a given control point is determined on the basis of neighbouring control points, as their difference i.e. for point p_i, is 0.5 $(p_{i+1} - p_{i-1})$. It has been illustrated in fig. 11. Tangent vectors in control points are parallel to the sections combining pairs $(p_{i+1} - p_{i-1})$.

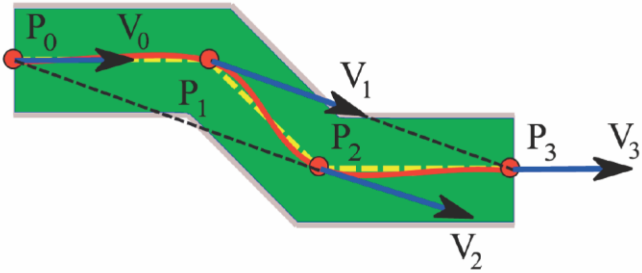


Fig. 11. Catmull-Rom curve as the trajectory of the wheelchair movement

The segment of such a cubic curve is defined with a formula (3) or in a polynomial form (4).

$$p(u) = [1, u, u^2, u^3] \begin{bmatrix} 0 & 1 & 0 & 0 \\ -0.5 & 0 & 0.5 & 0 \\ 1 & -2.5 & 1 & -0.5 \\ -0.5 & 1.5 & -1.5 & 0.5 \end{bmatrix} \begin{bmatrix} p_{i-2} \\ p_{i-1} \\ p_i \\ p_{i+1} \end{bmatrix} \tag{3}$$

$$p(u) = p_{i-1} + (0.5p_{i-2} + 0.5p_i)u + (p_{i-2} - 2.5p_{i-1} + 2p_i - 0.5p_{i+1})u^2 + \\ (-0.5p_{i-2} + 1.5p_{i-1} - 1.5p_i + 0.5p_{i+1})u^3 \tag{4}$$

Control points p_i of the curve in a 3D space has components *x, y, z,* i.e. $p_i = [p_{x,i}, p_{y,i}, p_{z,i}]$. Tangent vectors (velocity) in control points are derivatives of the curve *Catmull-Rom,* defined with a formula (5) and acceleration (6).

$$p'(u) = (0.5p_{i-2} + 0.5p_i) + (2p_{i-2} - 5p_{i-1} + 4p_i - p_{i+1})u + \\ (-1.5p_{i-2} + 4.5p_{i-1} - 4.5p_i + 1.5p_{i+1})u^2 \tag{5}$$

$$p''(u) = (2p_{i-2} - 5p_{i-1} + 4p_i - p_{i+1}) + (-3p_{i-2} + 9p_{i-1} - 9p_i + 3p_{i+1})u \tag{6}$$

Automatic and manual connection of the generated traffic trajectory has some advantages. It allows controlling traffic interpretation outdoor and moreover allows “reversing” the set of movements in an automatic manner so as to obtain the reverse trajectory of the wheelchair to the patient’s place of residence.

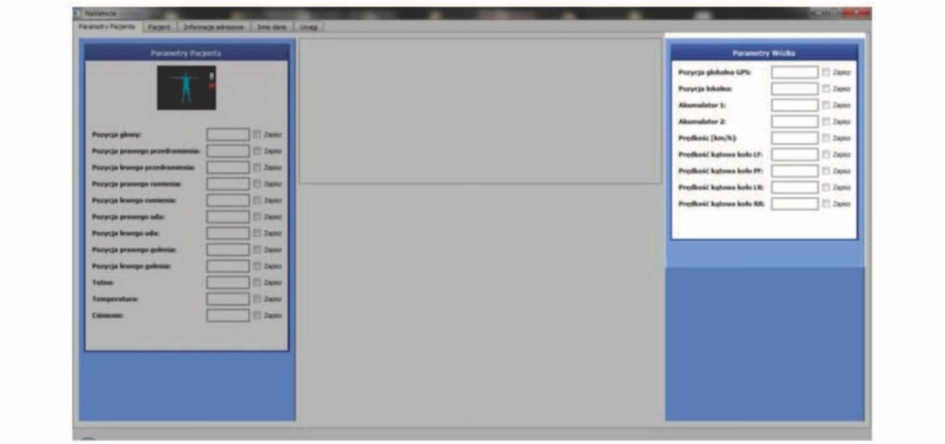


Fig. 12. Sheet of the current condition of the patient

The real traffic positioning of the wheelchair is determined on the basis of GPS measurements, corrected with a local gyroscopic measurement. The data is passed to the base station every 5 seconds so as the operator could trace the location of the wheelchair. Apart from the map, the data, in a numerical form, is displayed on the patient’s sheet, fig. 12. Visible in fig. 12, the field on the left includes data regarding the health condition (body temperature, blood tension, pulse), the field on the right includes data of the wheelchair defining its positioning and current technical state (engine power, temperature of crucial elements, configuration of the chair, state of the solar panels etc.)

Conclusion

The work presents results of one of the implemented tasks of the research project, regarding the development of a wheelchair for persons with a high level of disability along with the control and supervision systems. The entire project has been divided into several tasks, out of which four have been developed, two device-oriented (controller of the wheelchair, module of wireless transmission) and two software-oriented (component of the collision; wheelchair-environment, map editor - the task presented in the work).

The wheelchair along with high and low level software is a mechatronic device with a significant level of complexity. The discussed partial task regards planning the motion trajectory in a city on the basis of processed city plans in the form of bitmaps and with the use of cubic integrated polyamines for representing *Catmull-Rom*. The advantage of the representation is the automatic determination of velocity in hub points, thanks to which, the operator is not encumbered with this tiring and important task. The effect profiles are saved in the data base, connected with a patient and his wheelchair. The developed software implementing the aforementioned tasks has an operator interface with data sheets and the picture of the area map. The software was produced with the use of recognised standards e.g. free library of BOOST (software technologies, network layer), Qt (user's interfaces) and libraries OpenGL (graphical interfaces).

At present, there are works concerning algorithms solving problems and overcoming barriers by means of the wheelchair with a 4x4 permanent drive, with regards the idea of sliding.

After having performed at least 30% of the tasks, it is anticipated to obtain the external financial support which would allow building a prototype.

Summary

The work presents the author's conception of planning motion trajectory for a 'smart' wheelchair for persons with a high level of disability. The project assumes constructing a vehicle combined with a complex IT system which shall provide a great autonomy of motion (defining routes and traffic sections). The route is generated on the basis of processed city plans in the form of bitmaps with GPS markers, though the traffic route by means of cubic integrated polynomials for representing *Catmull-Rom*. The advantage of the applied method is the automatic determination of velocity at hub points. The effect profiles are saved in the data base, connected with a patient and his wheelchair. The developed task is the component of the supervision system of the wheelchair which is a complicated mechatronic system.

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Application of CAE systems for planning surgical operations

Jacek Cieślik*, Jakub Kasperkowicz*

Summary

The discovery of X-rays, the development of ultrasound systems, computed tomography and magnetic resonance significantly influenced the development of medical diagnostics. Accurate images of the human body provide a huge amount of redundant information. For medical doctors, this raises the problem to rapidly interpret the images and make a correct diagnosis. Right when the medical community needs it most, a support engineering software is introduced – the advanced CAE systems. It becomes necessary for physicians to use the engineering software. It is now used in hospital and clinical treatments worldwide. CAE system capabilities make it easier and speed up the elaboration of collected data. Before planning the operation, surgeons often carry out computer simulations, through which they can perform operations in a manner that is the least burdensome for both the patient and operator. They have at their disposal, not only virtual models of a real patient's body, but also the actual structure of the models obtained using virtual prototyping, which is a feature of a modern field of knowledge – mechatronics. This paper gives examples of planning operations using CAE systems.

Keywords: mechatronics, medical imaging, surgical operation planning, CAE systems.

1. Introduction

Presently, minimally invasive methods are more and more common with the tendency of topically located treatment. The procedures implemented in modern clinical practic include e.g. precise perforation of external coatings of the body with a needle or catheter in order to perform a biopsy, administering medicine or taking blood samples

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(fluids), criogenic and electrolite ablations, brachytherapy, deep brain stimulation, image diagnosis and a range of other minimally invasive surgery procedures such as e.g. laparoscopy, thorascopy. Modern medical instruments have features of mechatronic devices and are characterised with the use of advanced procedures in the scope of mechanics, automatics, IT and electronics. A significant element of the treatment process preceeding medical procedures is planning operations on the basis of image diagnosis [1, 3, 4, 5].

Medical diagnosis, thanks to advanced technologies of imaging, allows obtaining greater improvement of results while planning surgical operations. Medical knowledge has the greatest significance, however, more and more often it is connected with the use of engineering knowledge. It is essential for specialists to use computer applications. Computer programs are absolutely significant when it comes to processing complex images, which allow for the creation of 3 D models using medical radiation - scanning images from an ultrasonograph (USG), computer tomograph (CT) or magnetic resonanse imaging (MRI). Flat images of body cross-sections are processed by advanced computer systems into spatial, 3D virtual models. This is obtained thanks to new diagnostic capabilities. A human body, access to which was possible only by means of surgical tools, may undergo further non-invasive analysis and computer simulation with the use of methods applied in engineering analysis of materials and construction systems using CAE[1]. There is a possibility to precisly measure any required lengths, angles, shapes and capacity of organs or other objects, performing a simulation of the course of surgical tools as well as planning particular stages of an operation. This final process – pre-operative planning, has a significant meaning for laparoscopic or stereotactic operations inside the body of the patient. This example may rely on planning a pre-operative trajectory of a multi-part tool for surgical procedures presented in the work [8]. The existing computer software only partially satisfies the needs of doctors. Specialists from various fields of science work on mastering the existing solutions and developing new systems of medical diagnostics and pre-operative planning.

2. Diagnostic examination and medical imaging

Modern diagnostic examination composes of the systems needed to collect and process information. The most efficient tools are methods based on medical imaging, which constitute as images in the DICOM[2] format allowing e.g. browsing on the computer screen. Despite the fact that the same organ in various people may insignificantly differ by its look and size, thanks to medical imaging, it is known how a healthy organ should look like by using computer reconstructions. Imaging is connected with a patient’s organ which has lesions. Further, there is a transition to seek

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[1] Computer Aided Engineering.

[2] Digital Imaging and Communications in Medicine. The standard aimed at management, archiving, printing and transmission in the scope of medical imaging.

differences - lesions and defining their location. These actions have a significant meaning for stating a proper diagnosis and are required to plan a minimally invasive surgical procedure.

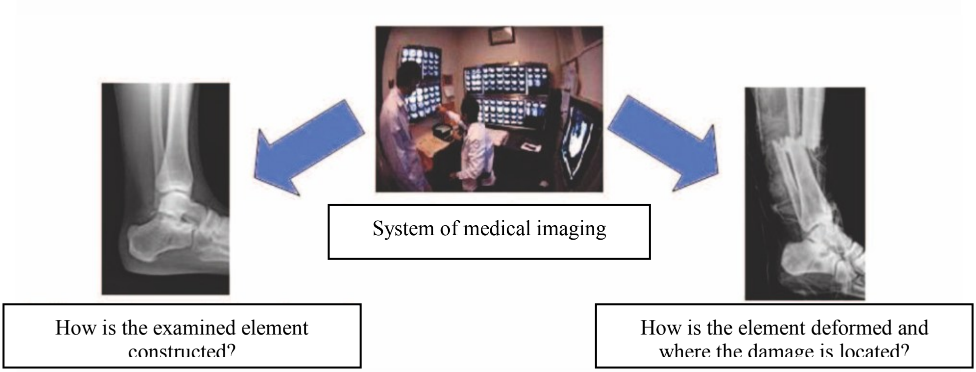

Fig. 1. Tasks of the medical imaging system [1], [12], [13], [14]

Modern methods of medical imaging, apart from morphological information (with a structure of tissues) may provide functional information not only on how an organ is built and located, but also about its funtions. The first device applied practically for non-invasive examinations was the X-ray. Previously, methods of medical imaging were not applied. Contact of the doctor with a patient for dignostic purposes was finished on the layer of an integument and touching palpation examinatin or observation of natural orifices of the body. The inside of the body was not available. Doctors obtained knowledge and experiments exclusively on the basis of previously performed operations. On the basis of palpation examinations and analytical research examinations, knowledge of anatomy was the basis of a diagnosis. The doctor stated hypotheses on the look of the lesions regarding organs inside the body of the patient. Apart from the study methods of X-ray radiation, significant progress relied on the introduction of ultrasonographic methods. Currently, medical imaging using methods of ultrasonography, CT and MRI consitutes a source of incredibly valuable information, authentic data on the condition of internal organs of the patient, and thanks to the ability of making rapid decisions, allows for life-saving procedures under critical conditions.

The methods of imaging examination are an important subject of the systems of medical IT. It must be emphasised that just collecting a great amount of data is not sufficient. More importantly is the knowledge of using that data and the assessment of its usefulness. In order to do that, diagnostic stations and special systems of computer diagnosis were developed to assist physicians in assessment, interpretation and use of collected medical images for diagnostic purposes.

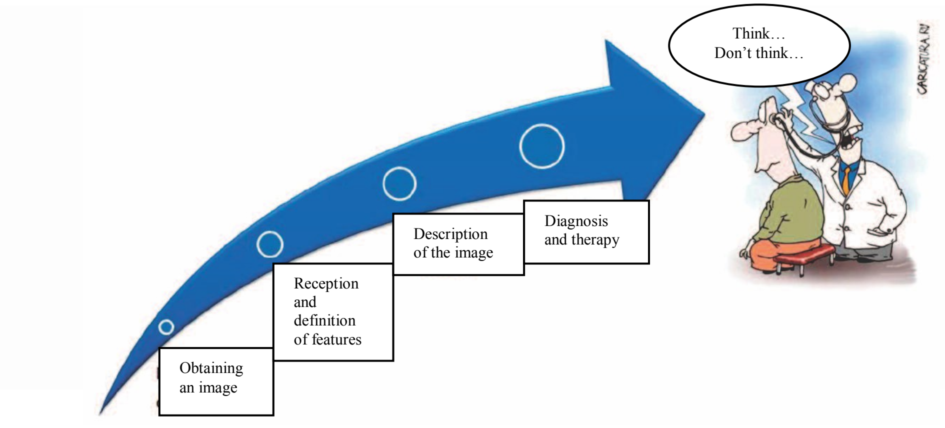

Fig. 2. The sequence of activities to obtain an image for using it in diagnosis[11]

Processing and managing obtained images is connected with their reshaping in a manner giving an improvement of their features in comparison to preliminary images obtained from the registering medical apparatus (CT and MRI). From the moment of obtaining the image to providing a diagnosis by a physician, there are a range of indirect activities performed. At the first stage, images are taken and defined by means of proper IT tools. Further, there is a stage of saving an image which has a key significance for further diagnosis and therapy. At the final stage of the diagnostic procedure, a final decision is taken by a doctor who bears full responsibility in the scope of further treatment of the patient. The responsibility cannot be borne by a machine, even equipped in databases with a system of artificial inteligence.

It should be emphasised that there is a surplus problem of imaging information. The problem is faced by a physcian who cannot know the way of using and interpreting the surplus of data - usually in the form of hundreds of images of body cross-sections. There are modern medical IT systems thanks to which it is possible to perform an automatic analysis of an image, select the parameters allowing defining physical features of the image and measure or visualise selected internal organs. Thus, having a lower number of ordered significant information, the physician may make a decision easier and more effectively. This is key for the health of the patient, rather than only an image coming directly from the source.

3. Selected programs for analysing images in medicine

Medical images are a significant source of information used by physicians in diagnosing diseases and the selection of proper treatments and planning operative procedures. The devices and diagnostic systems allow not only obtaining images (scans) of the inside of the body, but also by applying software for analysis, interpretation and advanced methods of image processing, they significantly increase their use for diagnostic purposes. Apart from simple operations such as the change in contrast and brightness or selecting edges of selected tissues, there is a range of more complex procedures influencing the quality improvement of the image, measured as the support for a psysician in dignosing on the basis of obtained images. Applications (IT systems) may be simple image browsers in formats compliant with DICOM, however, they have several specialist options. They allow to measure length, angles, diameter of organs and surfaces of their cross section, define the density of tissue, and create visualisation of entire organs and their systems e.g. digestive track or nervous system. There are applications with a very specialist and narrow purpose designed for selected diagnostic procedures e.g. to diagnose and define advanced cerebral tumours. These applications gives a possiblity of spatial modellling of internal organs, assigning them physical properties and their further complex virtual analysis with the use of the methods applied in the engineer analysis of CAE construction systems.

Applications designed for viewing, processing and analyzing medical images

On the medical IT system market there is a wide range of applications designed for working on medical images possessing various scopes of functionality. Apart from free browsers fit with a few basic functions associated with operating on the images, there are highly specialized programs, that except from browsing the images enable easy communication within the hospital database system, as well as image processing, analyzing and evaluating. The following are the examples of such programs:

- Dicom Works,
- Archmedic,
- eFilm.

Telediagnostics and decision support systems

Decision support systems (DSS) are active decision support systems. Equipped with medical sciences information, they generate diagnoses adequate to a given disorder on the basis of a patient’s personal data. Systems enabling remote medical consultations (telemedicine) are used as a support in the decision-making. The teleconsulting applications allow the doctors to the mutual consultation of patients’ results. The following are the examples of such programs:

- TeleDicom,
- DXplain.

Comprehensive image processing programs – CAE systems

Modern computer-aided engineering methods and systems are fast developing program group that should not be associated only with solving technological issues of the machine industry. The computer-aided engineering analyses (CAE) exceed such possibilities and employments. The achievements within the scope of FEM[4] analysis are essential for medicine purposes. Wide range of modeling and integration of

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[4] FEM – finite-element method, a numerical technique for finding approximate solutions to partial differential equations (PDE) and their systems.

medical software with engineering software gives additional, supportive effects. As a result, a synergy effect appears and causes the decrease in operation invasiveness, has a direct impact on operation and convalescence time shortage. The main advantages of the CAE system are presented below [1]:

a) Visualization and verification – due to special image segmentation tools, from 2D images one can create 3D visualization not only of an organ as a whole, but also its separate fragments.
b) Measurements – performing advanced geometric analyses: wall thickness, vessel diameters, vein and respiratory tract tortuosity, tissue porosity, bone joints condition, etc.
c) FEM analysis – simulations useful for blond circulation evaluation or vein and artery pressure determination. They help understand biomechanical phenomena, for instance walk mechanism, or assess implant functioning.
d) Implants and prostheses designs – thanks to the cooperation of technology and bioengineering, one may quickly produce and analyze a comprehensive prosthesis or implant project, as far as its structure and operation are concerned.
e) 3D prototyping - constructed models might be printed in 3D printers (so called Rapid Prototyping[5]). In case of skull bone (cranium) implant, it considerably shortens operation time.
f) Operation planning – in this respect the CAE programs display an exceptional usefulness. Due to computer modeling functions, the operation might be performed and analyzed on a pacient's virtual model.

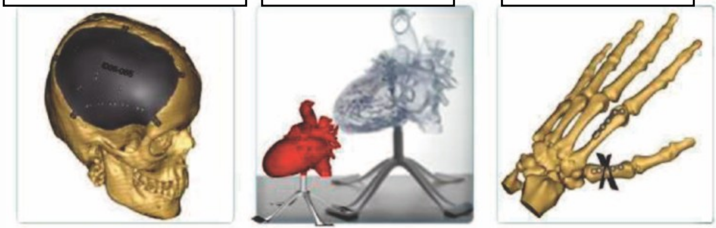
Examples:

- Mimic and 3-matic,
- Amira.

Visualizations and verification

Measurements

FEM analysis



Implants and Protheses Designs

3D Prototyping

Operation planning

Fig. 3. Examples of the CAE designing employment [9]

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[5] Rapid Prototyping – A group of methods for fast, precise and repeatable production of elements in additive technology, for instance with the use of stereolithography or 3D printing.

4. Mimic & Amira programs and CAE systems cooperation. Foot model analysis by means of finite-element method.

Foot model visualization allows every surgeon to plan and perform an operation. The surgeon may trace a virtual foot skeleton model on computer screen. According to this procedure he/she selects proper instruments, defines the way of their movements and performance of bone and cartilage surgery.

Pressure analysis on the surface of the foot might be used for diabetes advancement level determination. The test is conducted by means of a special measurement system, called paedobarograph. When the device is pressed with a foot, appropriate pressure force values are being visualized on the computer screen. Further FEM analysis enables modeling and simulations without employing additional measuring tools. Analysis of the foot underside surface pressure allows one to design a proper insole and select right materials in order to reduce the biggest local loads (pressures) of the foot. Another field, in which the foot model can be employed, is motion analysis and rehabilitation, for instance associated with professional athletes recovered from an injury.

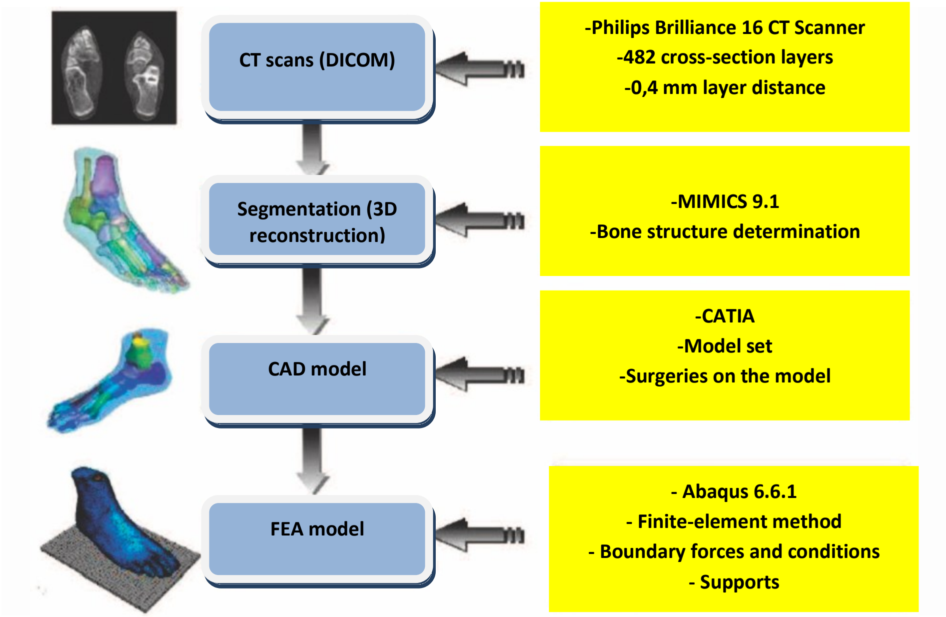


Fig. 4. Modeling process schema [9]

The geometrical complexity of the foot structure requires methods of inverse kinematics in order to obtain a model thoroughly describing a biomechanical behavior of the human foot – a system of soft tissues and bones. Obtaining proper results is possible throughout a creation of a detailed anatomical model and anthropometric features selection. The first activity is to get medical images of the foot's cross-section by means of a CT scanner and to process them to digital version, for instance in Mimic or Amira programs [2]. Then the created 3D model undergoes segmentation process. Having been transformed from the anatomical model to solid model, the object's export to the engineering environment (CATIA, Solid Works, etc.) is possible. In this environment, the particular foot elements are set together and numerous geometrical operations are performed. Later on, the solid model is moved to computing system (for example ABAQUS, NASTRAN), where it is prepared and subjected to further analyses (nonlinear model). Loads are defined, boundary conditions and tissues material properties are set (tissues density is calculated), appropriate supports are selected (determination of the foot-ground effect) and division into elements process is performed ("meshing" – elements "mesh" creation).

5. Creating a model in Amira system

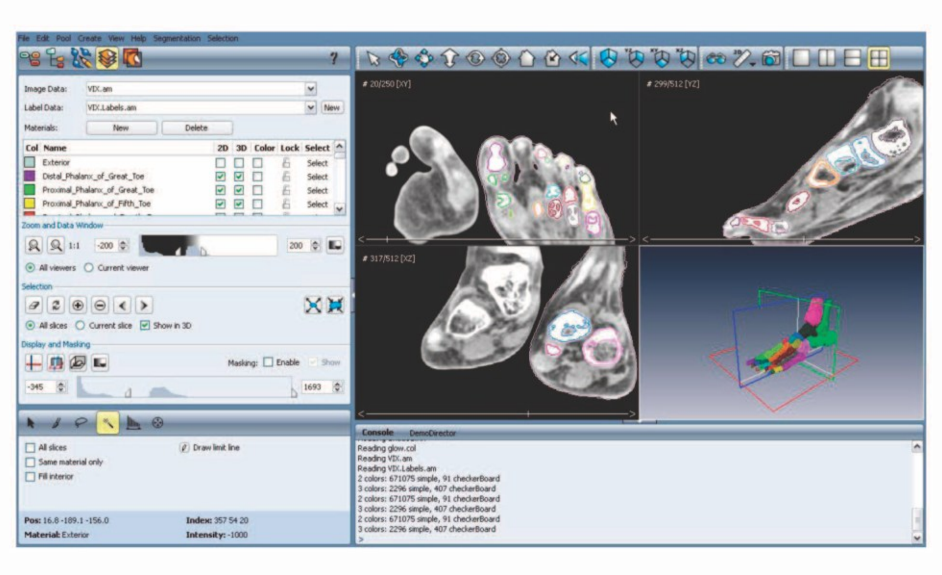
5.1. Preparation and data loading

In case of medical images one has to load a whole series of data, each of them is the next cross-section figure made during imaging. The images being loaded derive from foot imaging by means of a CT scan.

5.2. Image segmentation

Segmentation is a process dividing an image into smaller parts, often called regions, homogenous due to their special cross-sectional characteristics, such as greyscale level, colour and texture, or due to their future isolation. In comparison with the original images, the figures obtained by means of the segmentation process are simplified and contain considerably smaller amount of information. The medical images segmentation is an indispensable part of their computer processing.

The automatic element isolation process is used to analyze anatomical structures and tissues, to test brain activity or to find any pathological areas. The segmentation can also be employed as the first step to medical data compression. In case of imaging, when data variability can be extremely high, image segmentation algorithms – on account of chosen attributes – have to possess above-average flexibility and high efficiency. The segmentation is essential by reason of the possibility of emphasizing the most interesting image parts and useful during anatomical elements measurements on the basis of such figures. Information associated with length, angle and cross-section diameter might be particularly useful for a surgeon planning a surgery. The segmentation process is time-consuming. In order to isolate all foot parts in a thorough way, one should perform segmentation-based activities with precision and known the basics of anatomy. As far as Amira system is concerned, the particular process begins with marking a part of an image (so called voxel) and giving it a given label, describing the chosen material. Through abstracting from the next cross-sections of the same osseous tissue fragment and assigning them an identical label (one material), there is a possibility of creating a spatial representation. Moreover, through addition of subsequent materials one may separate next image fragments and, having assigned them various tinctures, cause that model elements will differentiate from each other.



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	Proximal_Phalanx_of_Fifth_Toe	☑	☑	☐		Select

-200 200

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● All slices ○ Current slice ☑ Show in 3D

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Fig. 5. Analyzing system module window of images designer for segmentation [1]

In a demonstration foot segmentation process, 28 bones and soft tissue have been isolated and the latter have been taken as a remainder of the whole foot part [1].

5.3. Forming a solid - spatial model

The completion of the segmentation process is followed by forming a solid model.. Having formed a surface network built of triangles, the model is subject to subsequent transformations. A complete surface model is essential for forming a volume model based on tetrahedrons.

5.4. Exporting of the model to Solid Works CAE computing environment

Surface models drew up in the Amira environment are saved as STL objects. Such files storage triangle surface structures and are compatible with the majority of engineering software CAD/CAE. With the aim of further analysis, one should convert STL files into solid objects, for instance into Solid Works system. The Solid Works system possesses a module enabling strength analysis and allowing detailed strength model tests. Having fastened a solid model describing a foot onto the floor and applied the pressure reacting into the bottom of the foot, strength analyses by means of FEM method begin. The simulation results of values and places of the greatest relocations were compared to the measurement results. The obtained values were in accordance with the values determined previously. Human tissues are characterized by a huge density diversity, due to which their strength properties are non-linear.

Fig. 6. A bone transparent model accompanied by a tissue model [1]

Fig. 7. A bone transparent model without a tissue model [1]

The above-mentioned way of conducting while performing FEM analysis might also be employed in obtaining different aims. Biomedical structures' properties analysis performed by means of computer-aided engineering systems is indispensable in tests of life forms tissues. FEM analysis results might be helpful in the following activities: detection and determination of a disorder's advancement level, operations planning, rehabilitation and bone elements strength testing, for instance after fractures.

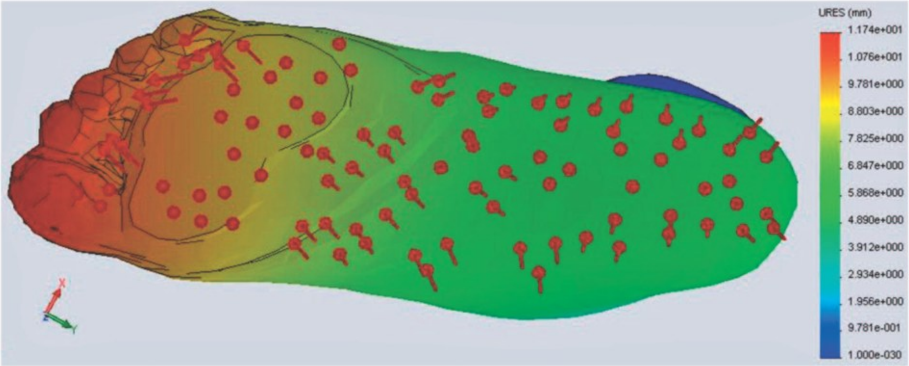

Fig. 8. Tissue FEM model (the bottom of a foot) under pressure [1]

The example [1] presented above raises an issue of relatively little complexity. Multitude of information obtained due to the employment of the computer-aided engineering, however, is useful to solving a series of unsolved problems. The basic task of the cross-sections gained through the tomography is to give a doctor an information about the tested structure. Transformation of flat images into a virtual model opens additional areas of activity.

The FEM method is a very useful tool to study the foot's biomechanics for commercial uses, especially for insole selection and its' stiffness optimization. The human foot's comfort depends on the pressure force appearing, when the foot touches a shoe. High values of the force cause pain or problems associated with the lack of loose blood circulation. The bones of the foot and tendons are able to balance the deformation and minimize the pressure force value. It appears from the physical relationships that the minimization of the pressure forces affecting the bottom of the foot is associated with the contact surface increase. Better comfort might be obtained by using properly and dynamically optimized insole, reducing the pressure forces. Geometrical complexity of the foot's structure assumes the employment of inverse kinematics employment in order to get a biomechanical model describing its behaviour (tissues and bones). Obtaining precise results depends on reliable anatomical model and anthropometric features selection.

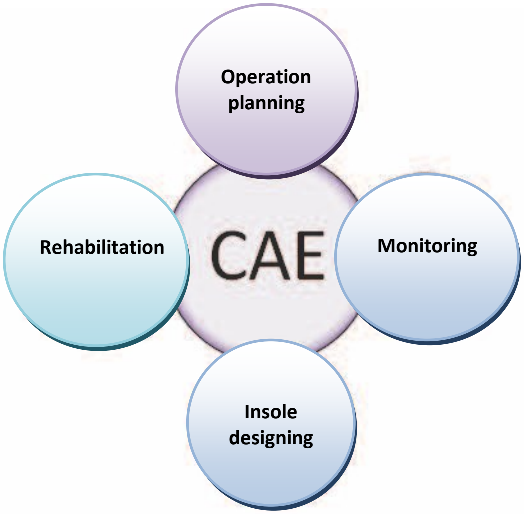

Fig. 9. Possible areas of use of the CAE software for the foot images

The FEM analysis is specifically employed in the foot's biomechanics and designing the Olympic runners' footgear because their feet are subjected to huge pressures, considerably bigger than in the case of casual running and walking.

6. Examples of the CAE software utilization in orthopedic surgeries planning

Operation planning is another wide-ranged aspect, in which the computer-aided engineering might significantly broaden its possibilities and hasten its drawing-up.

Let's consider an example of multiple ankle injury of a female tennis player. Having done the foot cross-section images (scans), a doctor might observe an existing deformation of ankle joint, but on the basis of the images he/she will not determine the risk of a new injury and point the place most exposed to it. As a prevention, he/she might recommend using a tourniquet and advise her against being a professional sportswoman anymore. The computer-aided engineering employment gives also additional diagnostic information. The foot images, collected and subjected to the virtual modelling process and the FEM analysis, will allow to point out the most weakened places in the bone structure. What is more, the foot motion biomechanical processes modelling enables one to determine in detail the force and stress values that might cause the next injury. The same procedure is used in the case of machines and devices, constantly monitoring their condition. Using the monitoring in medicine and rehabilitation, the risk of subsequent physical hurt can be minimized. The collected image data allow proper rehabilitation selection in order to improve its results. Doing the analyses periodically, one may check the changes undergoing in the bone structure.

Halluxes (toe deviations), a civilization degeneration, is analyzed as the next example. Deformations formed in the front part of the foot cause changes in its biomechanics and strong pain, as well as imbalanced weight division into the feet. The great toe, then, is not longer the main support while walking. The foot's structure stabilization and strength are considerably decreased and the muscles are weakened. This issue requires a complicated surgery. In this case, as in the former one, one should start with obtaining a set of CT scanned images that are to be later converted into a 3D model. The engineering software enables the division of particular bones and for performing necessary geometrical measurements, for instance lengths and angles. Carefully planned operation, reconstructed in a computer-based simulation will help avoid future mistakes during the real surgery. The doctor's training based on the computer simulation significantly shortens the operation time and, at the same time, increases both the patient's and the surgeon's convenience.

Another example is associated with a patient with an unstable thumb caused by the radiocarpal joint deformation [9]. Employment of the 3D visualization operation planning of the CAE system enables the simulation results to be used in the operating rooms. The images of the hand used by means of CT scan method and delivered to a surgeon-orthopaedist were converted into a 3D model. The doctor now can test several possible scenarios (operation methods) adapted to the patient's anatomical structure and the finger's deformation. On the virtual model the doctor determined the incisive surfaces and pointed out places and directions of incision during the surgery. On the base of such procedure, special tracks have been designed. They acted as a support for the most accurate incision possible during osteotomy. The tracks were made thanks to the print of the 3D-printer – this method is called "fast prototyping".

Fig. 10. Incisive surfa ces determination [9]

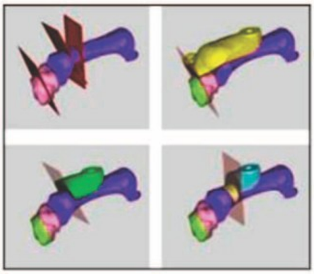

Fig. 11. Tracks designing [9]

The employment of engineering analyses to surgeries planning leads to the bigger precision of operation-connected activities, decreases the risk of unforeseeable injuries and post-operative complications.

Conclusion

The issues describe above present several examples representing the possibilities of the computer-aided engineering systems' medical employment. The development of image analyzing methods have significantly influenced the medical diagnostics advancement. Enormous amounts of data in forms of photographs – images scanned from ultrasound scanner (USG), CT scanner or magnetic resonance imaging (MRI) converted into virtual, spatial models. The models act as a base for future analyses, performed, for instance, by means of computer-aided engineering methods (CAE) or are used for forming real model structure, obtaining with the use of the virtual prototyping method, which is one of the main attributes of a new knowledge realm – mechatronics. The doctors face completely new possibilities of utilizing their medical knowledge accompanied by their engineering abilities.

Summary

X-ray discovery, ultrasonography systems, CT scan and magnetic resonance work-out had considerable impact on the medical diagnostics development. Detailed images of the human body give a great, excess amount of information. The following issue arises for a doctor-diagnostician – how to comment on the information and how to make a correct diagnosis. The computer-aided, advanced engineering methods (CAE) make an effort to meet the medical environment needs. The employment and use in hospital and medical treatment of the engineering software became the doctors' requirement. The CAE systems' possibilites make the study of data easier and faster and give the doctors numerous conveniences. Planning operations, the surgeons at first often make computer simulations, due to which they can perform surgeries in the least arduous way possible, both for the patients and for themselves. They may use not only the virtual models of a real patient's body, but also the real model structures obtaining by means of the virtual prototyping, which is one of the characteristics of a new knowledge realm – mechatronics. In this study examples of biological structures analyses and operations plans with the use of the CAE systems are presented.

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II

Modelling and control

Fast LMS algorithm in active sound control

Dariusz Bismor*

Summary

In this chapter a study on new, adaptive mechatronical system for active noise control system is presented. The inspiration for this study are substantial communication problems (including alert signal propagation) occurring in industrial plants with high noise levels. The adaptation algorithm used in this system is the LMS algorithm. The exact LMS algorithm stability criteria for the phase of fast adaptation are not currently known; there- fore an attempt to develop useful stability criterion is shown in this chapter. Performed simulations confirm validity of the new criterion. Moreover, the variable step-size algo- rithm developed based on the new criterion performs very fast and stable. Possible appli- cation of such system in form of personal, active hearing defender influences both the security and working conditions and therefore it is important for the national economy.

Keywords: mechatronical systems, active noise control, adaptive systems, LMS algorithm, stability.

1. Introduction

From the beginning of the 1990s. of the former century, mechatronics entered into a phase, in which a natural feature was equipping mechatronical systems with functions enabling them to advanced interaction with the users, often called intelligent functions [1]. The intelligence should be understood as a mechatronical systems capability to adapt to constantly changing user requirements and/or environmental conditions. Such adaptation is usually associated with advanced operational functions and digital signals processing. Forced by the market, such mechatronical systems function have caused that this particular branch of science is not longer the engineering domain and transformed into a scientific discipline.

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One of the modern aims of mechatronical systems is building user-friendly technologies that are able to adapt to the users' knowledge and ability level, as well as to influence the human development, so that the system human-machine efficiency will be constantly growing. Such mechatronical systems, often called 'human friendly and adaptive mechatronics' (HFAM [1]) will possess completely new, exciting properties. It would be impossible to achieve without methods and techniques based on self-learning, autodiagnostics, autoconfigurations and adaptation [2].

The mechatronical system complying with the above-mentioned aims is an active noise control system (ANCS). The main components of such system are microphones functioning as measurement detectors, microprocessor system processing the collected signals and calculating of operations, and speakers functioning as executing elements. The most common ANCS systems are noise control systems in waveguides, personal active hearing protectors, active headrests and systems creating noise zones in the rooms. Since the environmental variety, within which the ANCS system can be employed, is great, the microprocessor system has to possess a high level of adaptation to such conditions. Undoubtedly, the ANCS systems are the systems aimed at user work quality improvement through noise elimination. Yet, there is one more important feature of such systems: safety.

In order to understand the impact of the ANCS systems on safety improvement, one must realize that in numerous industrial facilities, the noise levels make the working and communication between the employees harder or even impossible. The communication is even more difficult because they must wear personal hearing protectors. In hazardous cases, the essential difficulty is the way of informing the workers in the endangered area about the necessity of leaving it. The examples of facilities of such condition are power plants, mills and mines. The mechatronical ANCS system flexibility depends on the ease, through which one can supply the personal hearing protector with voice communication module and alarm signals propagation module [3]. Due to them, the mechatronical system is used in the essential area for the economy.

The aim of this chapter is to show theoretical and simulation projects leading to drawing up of an adaptation algorithm able to work in the described above ANCS system. The algorithm should be characterized by high convergence speed and great stability. Unfortunately, the requirements are contradictory: high speed algorithms are low-convergent, while in the case of fast-convergent algorithms the instability risk is usually high.

2. Adaptive algorithms

Although digital signal processing is one of the most indispensable aspects of the mechatronical system for many years [4], the most intensive involvement of the specialists, who work on the processing of the digital signals into forming and developing such systems, has been observed in recent years. The intelligence and adaptive capability towards changing environmental conditions, set into the modern mechatronical systems, is very often associated with the necessity of adaptive algorithms use in operating mechatronical systems. The adaptive algorithms are the domain of the specialists who work on the digital sound processing. On the other hand, the mechatronical systems' requirements enable the ideas and algorithms to be employed in practice because they will never come out of the computer simulation phase. The existence of proper software and tools allowing using sophisticated algorithms in the mechatronical systems is also not insignificant.

The adaptive algorithms means every computer code that may undergo changes depending on the conditions, in which it was commissioned, or on the data it works on. Nevertheless, as far as this chapter is concerned, a narrower adaptive algorithm definition is employed –an adaptive filtration algorithm.

The adaptive filtration necessity is always connected with lack of complete information about the system, from which the signals are being filtered, or with the fact that the system is subjectto continuous changes. In such cases a natural approach should be linked with the filte tuning in at regular time intervals and in such a way, that in every stage the most up-to-date and greatest possible knowledge should be employed.

So as the tuning-in filter operation is not to be too expensive and be performed automatically, so called recursion algorithm is used. Such algorithm begins from particular values, called original values, that represent the knowledge of the system, possessing at the beginning of the adaptation process. Then, in every adaptive step, the algorithm inserts into the filter changes associated with new system information, in which the filtration is performed.

The employment of property configured adaptive algorithm in the unchangeable system leads to finding a filter similar to the optimal one (giving the best possible results). In the unchangeable environment, however, the adaptive algorithm allows to trace these changes and coping with them.

One of the most commonly used adaptive algorithms are recursion method, called a recursive east squares method (RMNK or RLS), and LMS algorithms (LMS – least mean squares).

The east mean squares gives the result – as the name itself indicates – being the mean square optimization resultant (a better name would be "the least square sum method"). This method originated in the late XVII century, and its author is supposed to be Carl Friedrich Gauss [5]. The method and its employments gained particular interest in the second half of the XX century (for instance [6]). Nowadays it is relatively well known from the theoretical point of view. For example, a mechanism of forming a negative phenomenon called "an estimator explosion" has been known so far, just like the means of preventing it [7]. The most important disadvantage of the RMNK method is huge, square, computing complexity: increasing the filter's dimensions twice, the number of computings performed in every step increases four times. What is more, this method is prone to numerical errors.

The LMS algorithm is probably one of the most commonly used adaptive methods. The majority of the readers probably use the LMS algorithms in one of its applications, that is an adaptive echo deletion in mobile phones. The main advantages of the LMS algorithm are: implementation simplicity, calculation speed and remarkable immunity [8]. Despite the mentioned simplicity, a detailed mathematical analysis of this algorithm is currently unknown [7]. Many scientists are still researching in order to show the analysis of the LMS algorithm, that will enable the best possible use of it. A fragment of such analysis is presented in the following part of this chapter. Deliberation will be limited to the LMS algorithm employment to the filter adaptation of a finite impulse response (FIR). It is a filter, the output of which is associated with its parameters according to the formula presented below:

$$y(i) = w_0 u(i) + w_1 u(i-1) + \ldots + w_N u(i-N) = \sum_{n=0}^{N} w_n u(i-n) \tag{1}$$

where *N* is the filter length.

3. The LMS algorithm and its employments

The LMS algorithm application to the FIR filter adaptation leads to the following equation of the filter's parameters updating:

$$\boldsymbol{w}(i+1) = \boldsymbol{w}(i) + \mu \boldsymbol{u}(i) e(i) \tag{2}$$

where:

$\boldsymbol{w}(i)$ *– filter parameters written in the vector form,*

$\boldsymbol{u}(i)$ *– input data written in the vector form,*

e(i) – algorithm error

μ – step length.

An algorithm terror is usually calculated in the following way:

$$e(i) = d(i) - y(i) = e(i) - \boldsymbol{u}^T(i)\boldsymbol{w}(i) \tag{3}$$

where *d(i)* represents a signal of desired properties, so such signal, into which the filter's output should become similar. As a result the error will equal zero.

The main problem and drawback of the LMS algorithms is the necessity of the step length thorough selection (μ). Too short step causes that the filter adaptation speed becomes too slow. On the other hand, step too long causes that the filter error in the steady-state (when there are no changes in the system) is too great. What is even worse, the latter might lead to the whole algorithm's destabilization.

In some applications the convergent and LMS-tuned filter's low speed is not so important – stability is a priority. There is a group of applications, however, in which the algorithm's convergence speed is a priority. An example of such application is noise control system in greater industrial facilities. The aim is to form a silence zone keeping up with a person moving in a large room. Therefore, the adaptation algorithm has to be fast enough to adapt the system to the person's motion changes and changes associated with machines switching on and off or the room door/barriers opening and closing. In such applications, a knowledge of the longest step is indispensable. It might be employed without any risk of the algorithm's loss of stability.

Two types of the LMS algorithm stabilization analyses can be found in the literature. The first one, popularized in the 70. of the former century by B. Widrow [9] is called an *independence theory*. This method is based on the assumption, that the input vector sequence (***u(i)*** vectors) is an independent, identically distributed sequence (IID sequence). This particular analysis method is used in some LMS algorithm applications, for instance for adaptive forming of antenna array signal, in which in all consecutive steps the algorithm operates on a set of independent data. Nevertheless, in numerous typical applications the LMS algorithm input data comes from a delay line:

$$\boldsymbol{u}(i) = \left[u(i) \;\; u(i-1) \;\; u(i-2) \ldots \;\; u(i-N) \right]^T \tag{4}$$

In other words, the input vector contains another samples of the same signal. In every successive iteration the oldest sample is removed, while all other samples are "moved down" and the newest one is added on the "bottom" of the vector. Therefore in two consecutive steps, vectors ***u(i)*** and ***u(i+1)*** are statistically independent because they contain the majority of the same samples! The independence theory is of no use here.

The second LMS algorithm stabilization analysis method is based on the so called *small step length assumption*. According to it, the analysis is correct only when a step is short enough to treat the LMS algorithm as a low-pass filter. The next assumption of this analysis is that an input signal *u(i)* and a signal of desired properties *e(i)* should be stationary and Gaussian combined [7]. A result of the analysis based on the small step theory is usually a commonly quoted LMS algorithm's stability condition, shown in the following formula:

$$0 < \mu < \frac{2}{\lambda_{max}} \tag{5}$$

where λmax means a maximum eigenvalue of the input signal autocorrelation.

Neither the analysis based on the independence theory, nor the analysis based on the small step theory are not used in the situation, when the LMS algorithm remains in a fast adaptation condition. What is more, both analyses assume the input signals stationarity (their statistical properties invariability) – this premise is not fulfilled in numerous typical applications, too. For instance, in the discussed active noise control application the input signal is not stationary if consecutive machines are continuously switching on and off. Therefore, an attempt of working out a different, based on a lesser amount of assumptions, LMS algorithm stability condition has been made. The next subchapter presents the results of this test.

4. The LMS algorithm stability condition

The employment of a new condition requires the following assumptions:

- input signal *u(i)* and signal of desired properties *d(i)* are signals of real, deterministic and random values,
- if a signal is deterministic, its values are limited,

- if a signal is random, its probability distribution function is limited,
- a signal's output might be shown in the following formula:

$$y(i) = w^T(i)u(i) = \sum_{n=0}^{N} w_n(i)u(i-n) \tag{6}$$

One must pay attention that these assumptions are much weaker than the assumptions of the independence theory or the small step theory. The first three ones describe the signals used in the majority of the LMS algorithm applications in an excellent way. The last premise is that the filter's *y(i)* output is a result of the input filtration *u(i)* through the FIR filter of finite number of variables during parameters.

Replacing the error equation shown at the beginning of the precious subchapter with an equation describing the LMS algorithm operation, one may obtain:

$$w(i+1) = w(i) + \mu u(i)\left[d(i) - u^T(i)w(i)\right] \tag{7}$$

After its components' reorganization, the equation presented above might be written as follows:

$$w(i+1) = \left[1 - \mu u(i)u^T(i)\right]w(i) + \mu u(i)d(i) \tag{8}$$

The above equation might be treated as a discrete equation of a non-stationary object condition. A general form of such equation is:

$$\tilde{x}(i+1) = A(i)\tilde{x}(i) + B(i)\tilde{u}(i) \tag{9}$$

while at the same time, non-stationary matrixes ***A(i)*** and ***B(i)*** (subjected to time changes) in the given case take on the following values:

$$\begin{gathered} A(i) = 1 - \mu u(i)u^T(i) \\ B(i) = \mu u(i) \end{gathered} \tag{10}$$

Since the stability of the system described by means of condition equations depends of the ***A(i)*** matrix, this particular matrix will be called a *LMS algorithm stability matrix*.

Presentation of the LMS algorithm stability conditions requires the revision of the two theorems of the control theory [10]. These theorems are associated with stationary systems and their adaptation towards the given instance is presented below.

Discrete system stability

The system described by a condition equation is stable (on the stability limit) only when all elements z_1, z_2,…, z_k of a condition A matrix minimal polynomial have modules not bigger than 1 and when each element of module equaling 1 is a single element of this minimal polynomial.

Inconvenience of the above-mentioned theorem is that it requires finding out of a matrix minimal polynomial [11], which is uneasy in general.

Stability of discrete systems with symmetrical condition matrix

The system described by a condition equation, in which a condition A matrix is a symmetrical matrix ($A^T=A$*), is stable (on the stability limit) only when all elements* $z_1, z_2, \ldots, z_k$ *from a characteristic polynomial have modules not bigger than 1.*

In the given case a LMS algorithm specific stability matrix form (which is a condition matrix) causes that this matrix is always symmetrical. Due to this fact the stability analysis can be performed on the basis of the characteristic polynomial elements, that is on the basis of the LMS algorithm stability eigenvalues.

Unfortunately, in this case the $\boldsymbol{A}$ matrix is also a non-stationary matrix. As a consequence, employment of the criteria presented in the above necessary and sufficient conditions results in obtaining only sufficient stability condition.

The author of this chapter has been successful in proving, that as far as the LMS algorithm stability matrix is concerned, all its eigenvalues, except one, equal 1 [12]. Therefore, the stability will be dependent on this particular one eigenvalue, shown in the formula below:

$$\lambda_1 = 1 - \mu \sum_{n=1}^{N} u^2(i-n) \tag{11}$$

Meeting the sufficient stability condition requires this value to be lesser than the unity, in respect of a module; that is, the sufficient stability condition might be presented in the following formula:

$$0 < \mu < \frac{2}{\sum_{n=1}^{N} u^2(i-n)} = \frac{2}{\|u(n)\|^2} \quad \textit{for every (i)} \tag{12}$$

5. Variable step-size LMS algorithm

On the basis of the sufficient condition shown in the previous subchapter, the variable step-size LMS algorithm has been formed. This algorithm selects the step length in each iteration in such a way, that it would be equal to maximum permissible on account of the value stability multiplied by a scale coefficient ε:

$$\mu(i) = \varepsilon \frac{2}{\sum_{n=1}^{N} u^2(i-n)} \tag{13}$$

Due to this scale coefficient, value of which must be lesser than 1 for the algorithm's stable work, one might influence the adaptation speed without any stability losses.

The VS-LMS algorithm has been employed in active noise control simulations accompanied by non-stationarity in the original track. The algorithm operates in the following way.

Having detected changes in the simulation model, the coefficient ε value is increased to 0,9. Such a value is maintained during 4 consecutive iterations. The coefficient is then decreased to 0,35, a constant value, when in the simulation model there are no changes.

Since the experiments have revealed that a sudden change of the scale coefficient is unfavorable to the algorithm, the coefficient decreasing undergoes gradually and is realized through multiplying its value by 0,99 in each subsequent iteration.

One of the simulation issues was acoustic environment non-stationarity modeling which is used for instance during human movements in rooms. The problem was solved by simulating a system of switching filters accompanied by polishing – a Simulink implementation of this idea is shown on fig. 1.

The simulating system of switching filters contains ten electroacoustic paths models in form of FIR filters. Every model has been identified on the basis of real data collected off-line from various measurement points located along a college corridor. The corridor is 25 m long, 2,5 m wide and 3 m high. The measurement points were away from each other of 0,5 m and located along its length in its middle part. Sampling rate equaled 1 kHz and every filter had 300 parameters.

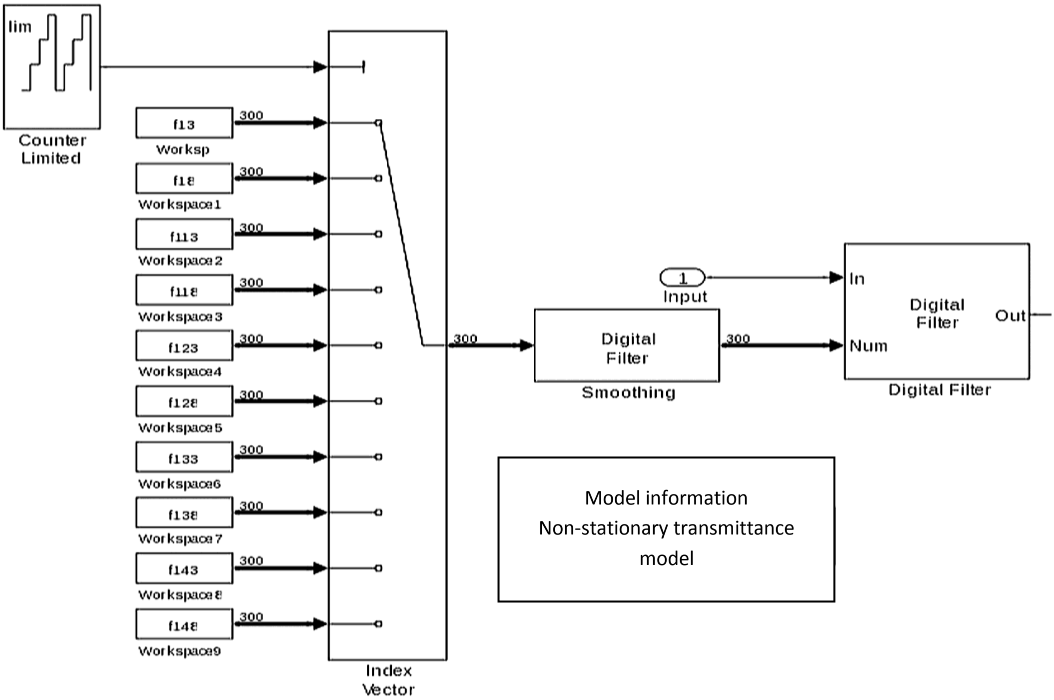

Fig. 1. A Simulink schema of non-stationary original path model

Switching occurred every 3 seconds. Moreover, the filter's coefficients changes were not abrupt, but they were polished by means of a individual filter of transmittance for every coefficient:

$$K\left(z^{-1}\right)=\frac{1}{1-0{,}8z^{-1}} \tag{14}$$

The proposed variable step-size LMS algorithm's behavior has been compared to a normalized LMS algorithm (NLMS) behavior, which is the most commonly used variable step-size LMS algorithm [7]. In both cases the noise controlling filters were 512 parameters long, a typical length for active noise control applications. In order to compare operations of these two algorithms, two indicators were used: control obtained by the end of the experiment and total variance of controlled signal, calculated during the whole experiment. The latter was chosen because the main aim of the new algorithm is to maintain a significant, but above all a constant noise control during the algorithm's operations. In other words, this indicator shows noise risk of a man being within the range of the active noise control algorithm in a better way. Furthermore, the control value obtained at the end of the experiment depends on the moment of its stoppage, since in the shifting models experiment there is no complete steady-state.

6. Non-interfered simulations

In the first experiments an input signal consisting of two sine curves was employed: the first on of 225 Hz frequency and 10 level, the second of 4000 Hz frequency and 1 level. The input signal did not consist of hardly controlled white noise. The experiment's results are shown on figures 2-4.

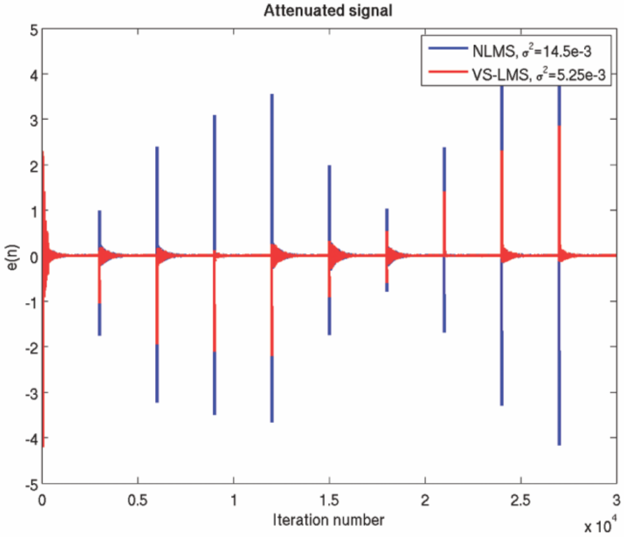

Fig. 2. Controlled noise timing in the first experiment

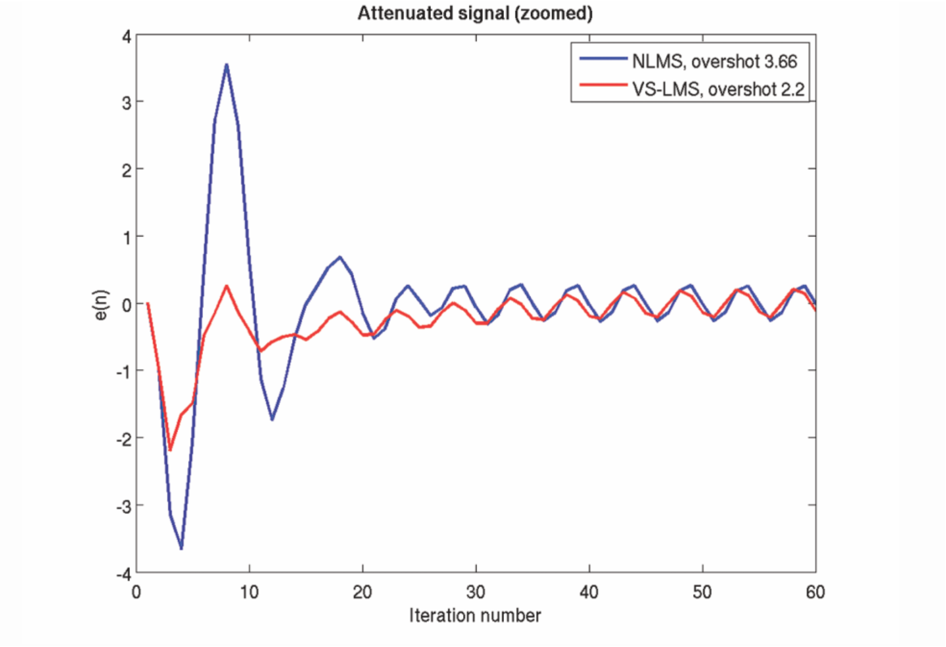

Fig. 3. Magnification of the chart fragment of figure 2

Controlled noise timing for the NLMS algorithm (blue Line) and for the proposed algorithm (red line) is presented on figure 2. In the picture one can easily see the moments of non-stationarity (changes) in the original path model – these are the moments, in which “pins” are seen in the controlled noise course. At the same time one can observe, that in the case of the proposed algorithm the “pins” height is lower than in the NLMS algorithm instance. It is proved by the value of the calculated indicator in form of signal variance during the whole simulation period: it has amounted to 5,25 ·10-3 in case of the proposed algorithm and 14,4 ·10--3 in case of the NLMS algorithm.

Magnification of the signal parts of figure 2 is shown on figure 3. It occurs that the “pin’s” height, formed during the proposed algorithm operation (2,2) is considerably lower than in the case of the NLMS algorithm (3,66). What is more, the proposed algorithm, apart from the NLMS, did not “produce” the second readjustment (of the “pin”).

Step lengths of the proposed algorithm during the simulation phase are shown on figure 4. The greatest step-size values reached up to approximately 7 ·10-5 and were accepted during the 5th iteration, after non-stationarity in the original track. It allowed to quick retuning of the filter and, as a result, quick muffling of the “pin” within the noise control timing. Then the step length was gradually decreased, until it reached around 2,7 ·10-5. This last value allowed to obtain great attenuation in such timings, when there were no changes in the model.

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* the final version of this study is available on the website www.inprona.pl

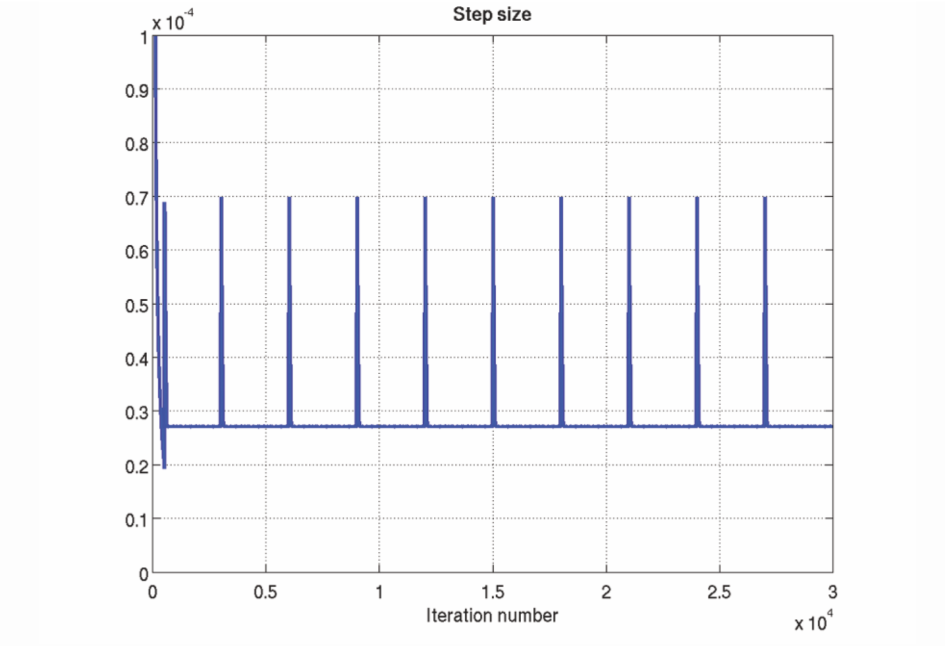

Fig. 4. The algorithm step lengths during the first experiment

7. Interfered simulations

The next experiment was conducted with the use of the same input signal, but with an additional white noise. The results of this experiment are shown on figures 5-7.

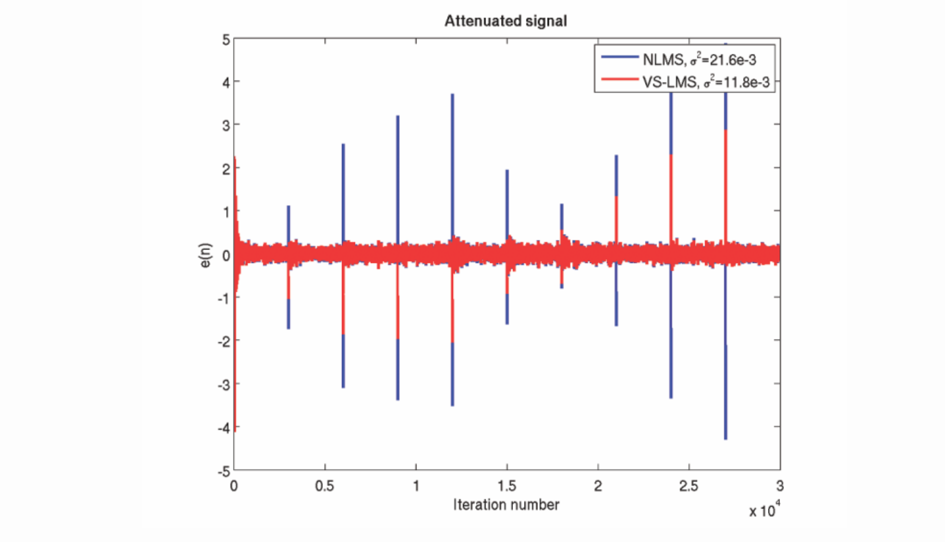

Fig. 5. The attenuated signal timing during the second experiment

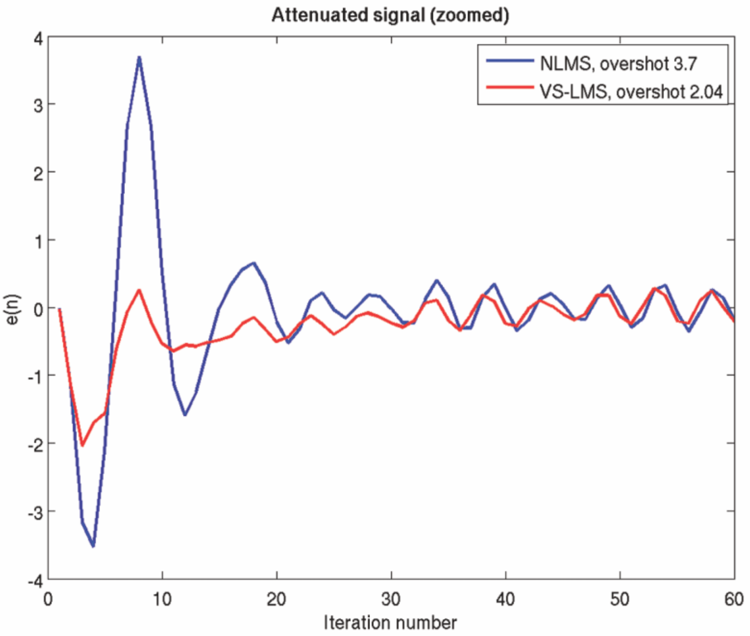

Fig. 6. Magnification of the chart fragment of figure 5

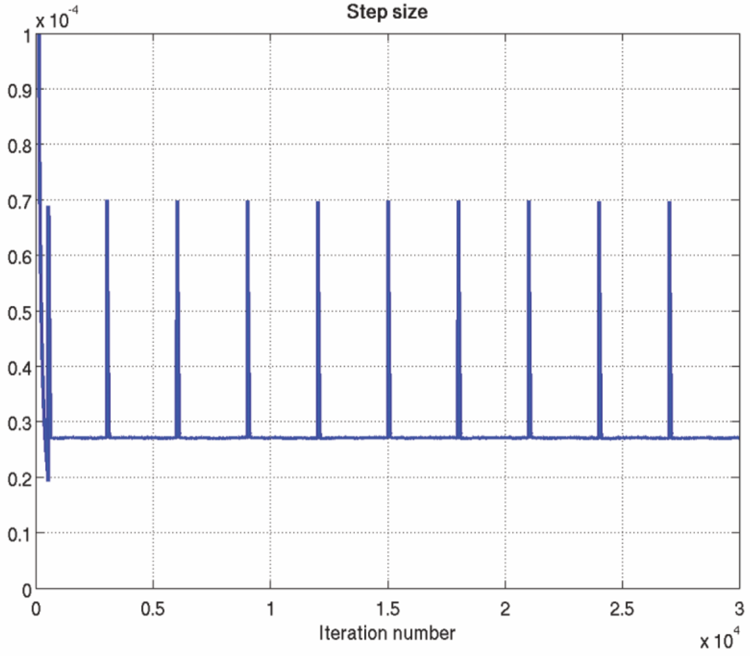

Fig. 7. The algorithm step lengths during the first experiment

The addition of white noise to the attenuated signal did not affect negatively the proposed algorithm efficiency: total variance during the experiment amounted to 11,8 ·10-3 in the case of this algorithm, in comparison with 21,6 10-3 of the NLMS instance. What is more, the proposed algorithm still better attenuates the “pins” formed after the changes in the original track being modeled, what can be clearly seen on figure 6. The increased variance value is then only a result of the white noise existence in the attenuated signal. At the same time neither the first, nor the second algorithm cannot attenuate this noise in an efficient way.

Step lengths accepted by the proposed algorithm are shown on figure 7. As can be seen, there are no significant changes compared to the noiseless experiment. It arises from the considerable length of the active noise control filter.

Summary

This chapter presents tests aimed at modern, adaptive mechatronical system forming, designed to active noise control. An inspiration of such system are major communication errors, including alarm communication, between the facilities’ workers. The LMS algorithm is an adaptation source, for which the stability condition for quick adaptation phase. might be planned. This chapter tries to show such a condition. The conducted simulations prove in an experimental way the correctness of the stability value and high algorithm speed with variable LMS. The employment of such system, in form of a personal, active hearing protector, is vital to the economy due to safety and work efficiency improvements.

Acknowledgements

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Adaptive control in mechatronical systems

Paweł Kos* Lucyna Leniowska*

Summary

The vibrations of machine components like plates may have significant, negative influence on working of the tool, because they cause reduction in the effectiveness and durability as well as worsening the working conditions (noise). This chapter deals with the idea of mechatronic system construction for vibration reduction of the plates, which are often elements of industry machines, cars, ships, airplanes, building constructions and white goods. In the proposed solution, qualified as active vibration control method, the adaptive algorithm was applied. The main advantage of this method is the ability to automatically upgrade the parameters of the controller to the current work conditions, on the basis of the measured input and output signals. This fact gives wide perspectives for using the proposed solution in industry, especially in case when work conditions of machines change quite often, because it causes significant reduction of the cost of the operator work, which should be done in order to change the parameters of a classic controller.

In the proposed mechatronical system the PC computer with data acquisition expansion cards was used as a control unit. It was controlled by real time operating system RTAI-Linux. The conducted examinations, which were made using MATLAB/SIMULINK and the designed application, show that the presented system causes significant vibration reduction of the considered circular plate.

Keywords: mechatronical systems, adaptive control, active vibration control, RRLS algorithm, RTAI-Linux, OMAP microntrolers.

1. Introduction

Mechatronics is a synergic connection of such classical knowledge domains as: mechanics, electronics, automatics and computer science, in every stage of forming intelligent electrical engineering systems e.g. in modeling, analyzing, designing and

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producing. This relatively new domain have evolved in the last several dozens of years, becoming the keynote of the computer-aided engineering. Through integration of the most advantageous constructing solutions, analyzed on the basis of the virtual prototypes and modern technologies, mechatronics enables realization of high-quality products, at the same time guaranteeing the increase of efficiency and reliability of their operation, as well as reduction of time and financial resources for their production.

Due to the fact that the modem machines are controlled by means of specifically selected algorithms of automatic regulation, implemented with the use of both computer science solutions (industrial computer, real-time systems, software) and analogue and digital electronics (measurement and performance chain elements), mechanical designing of such systems can no longer be isolated from the mentioned aspects of their operation. Applying the idea of mechatronical designing, one adopts a unified approach aimed at a device's component and functional integration in all stages of its manufacturing.

2. The notion of a mechatronical system

A general structure of a mechatronical system is presented on figure 1. Process data are obtained by measurement of its mechanical parameters, such as: deformation, speed, weight, temperature, pressure, etc., by means of detectors processing the value of measured physical quantity into an electrical signal. Such signals, together with a reference signal, act as a base for control signal determination, transmitted to properly selected "executive" elements – actuators. Control signal value determination is done on the basis of the designed controlling algorithm, implemented into a control unit. This unit very often realizes additional functions associated with operational interface that enables supervision over the controlled process's basic parameters, as well as modification implementation into the controlling algorithm.

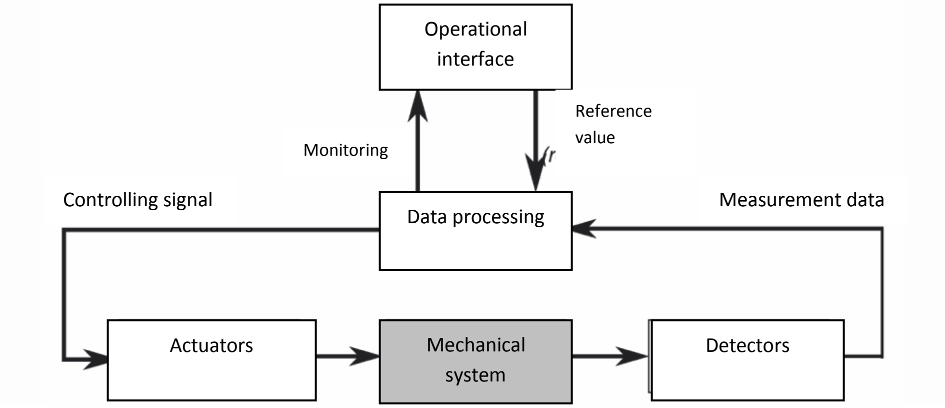


Fig. 1. Mechatronical systems working principle [2]

The presented idea of mechatronical systems designing leads to a significant increase of their functionality through:

a) Function integration

In the mechatronical systems, the mutual component cooperation within the scope of mechanics, electronics, automatics and computer science is essential. Employment of proper detectors, amplifiers and electrical actuators enables a device structure to be considerably simplified, compared to a clearly mechanical approach (for instance digital clock or camera). Further construction simplification is possible due to microprocessor solutions accompanied by decentralized electric drives, such as in digital sewing machines or automatic transmissions.

b) Greater possibilities of process control

Feedback system control, in which the controlled variable is positioned, sped up or forced, allows not only to reference value exact copying by a mechanical system, but also leads to linearization of characteristics. Due to this fact a significant construction simplification and production costs reduction occur (in comparison with classic, mechanical systems).

Mechatronical control systems development carries an increased amount of employed sensors, actuators, control units and, as a result, an increased amount of connections between these elements. This process has a great impact on a series of parameters, such as: devices weight and dimensions, necessary assembling area or production costs. Therefore, construction of a proper main system in the mechatronical and redundant systems, as well as reconfigurable electronic components, is a big challenge for the designers.

c) Addition of new functions, unavailable in the mechanical systems

Due to the application of synergic connection of solutions from various knowledge domains, the mechatronical systems allow to add numerous new functions, previously unavailable to classic mechanical solutions. One of the main features is a possibility of system control on the basis of physical quantity calculated by measured signals, for instance automobile control systems based on tyre slip, air pressure and temperature measurements. The next new function is associated with the adaptive control employment enabling system control adaption to working conditions subjected to constant changes. Such an actualization occurs automatically on the basis of measurements performed during the process. The systems transform into “intelligent” systems in the way described above.

In the furthter part of the chapter own mechatronical system with adaptive control is presented. It has been designed with the aim of active vibration control.

3. Active vibration control mechatronical system

Taking into consideration all above-mentioned features of mechatronical designing, active vibration control system of thin plates has been worked out. The plates are very often the industrial machines' vital parts. Vibrations of such structures are undesirable in many cases, influencing their efficiency and decreasing the device's operation (noise). They can also weaken their construction strength, etc. The elimination should be considered both in the designing and the employment stage. Commonly used before, yet uneasy to implement and usually expensive *passive methods*, appear to be not efficient enough within the scope of low and medium frequencies, so a typical "working" range of vibrating plates. An increasingly common alternative are active methods, such as adaptive control analyzed in this chapter. The essence of this technique is to put additional forces/moments setting off the structure's vibrations into the system by means of properly selected actuators. Values of such forces are calculated with the use of a given control algorithm and on the basis of measurements taken in the regulation system.

A detailed system structure and results of simulation and experimental tests are presented below. In the designed construction a PC computer with real time operating system RTAI-Linux was taken as a control unit. On the basis of available library functions, a software implementing the adaptive control algorithms on the given platform has been worked out.

3.1. Adaptive control

Control with feedback is based on employment of regulators with reference structure and parameters appropriate for a given plant model. Selection of the regulator's settings (so called tuning) enables obtaining the following features:

- stable system operation,
- desired properties of the controlled variable keeping up with set point,
- desired properties of noise reduction affecting the controlled variable.

In the regulator synthesis chase, however, simplifications of the plant model occur more than often, for instance by means of frequencies range narrowing and avoiding effects beyond a given range. Other factors having an impact on the regulator's efficiency decrease might be the plant's dynamic properties changes, arising from:

- non-stationarity – the object's properties change in time, for instance through ageing and the elements' wear and tear,
- non-linearity – the object's properties for small deviations from the given working point change considerably,
- random interferences – the features' impact on the object is hard to foresee.

Due to the employment of feedback loop, a system with the regulator switched on and of constant parameters possesses a „natural" immunity to error made during its synthesis, e.g. structural errors and the object parameters' changes. The immunity is limited, however, and causes that huge structural errors or its different properties may lead to the device's efficiency decrease. In extreme cases it even may cause stability loss of the whole system. Then one should retune the regulator, which is a time-consuming activity more than once requiring the process stoppage and qualified personnel presence.

One of the alternative method enabling the solution of the above-presented issue is the adaptive control employment. *Its essence is based on automatic adjustment of the regulator's parameters to the changing object properties and its environment* [7]. The main aim of the adaptive system operation, considering in this chapter, is gathering information about the regulated object and the object model identification on the basis of the conducted measurements. Working principles of such system are presented in the figure below:

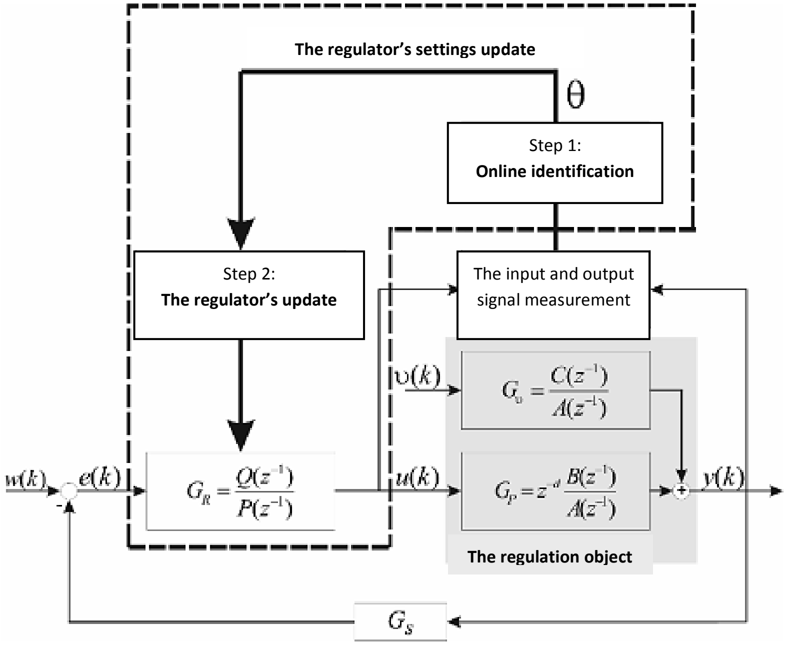


Fig. 2. The adaptive algoritm's working principles

In the presented system, the regulator's parameters are indirectly set on the basis of the previously determined in the identification process in online model mode the plant. The identification for the object working in the negative feedback loop, which means that the model is appointed on the basis of current controlling variable *u(k)* and controlled variable *y(k)* measurements.

An unquestionable advantage of the adaptive control is its versatility that might be seen both in applying this method to controlling multiple processes, and in parameters changes detection capability, which are the effects of outside factors. The listed characteristics, however, are paid with a significant increase of the computational complexity of used algorithms. Intensive development in electronics and computer science in recent years gives real opportunities of forming "intelligent" mechatronical systems operating on the basis of the adaptive methods. This fact causes even broader employment of the adaptive control in various industrial branches, starting from the aerial industry, in which this particular way of control was implemented for the first time in the 50s. Nowadays these methods are employed for instance in the autopilot system, in the car industry in the Adaptive Cruise Control (ACC) which supports the traditional car control system thanks to automatic adjustment of its speed and distance from the preceded automobile, in the industrial machines – the adaptive control of CNC lathes, but also in the modern agriculture, for example in thermal and mass regulation processes control, in specialist agricultural facilities (greenhouses, mushroom-growing cellars) in order to maintain the optimal plant growth [10].

3.2. Plant model's identification

According to the schema show on figure 2, the adaptive control algorithm can be understood as a connection of two subsequent steps:

(1) the plant's model identification,
(2) the regulator's parameters update.

In the first step of the presented procedure the model's set structure parameters values setting, working in the feedback loop, thus in the regulation process, is being realized. The model is set on the basis of the following measured values: control signal *u(k)* and controlling variable *y(k)*. Since these two signals are dependent from each other (the regulator determines the dependence), in order to identify the object by means of known identification methods in *offline* mode, the particular identification conditions must be met [3]. It means that the regulator's structure should be set and that the regulator itself should be of the higher-order in comparison with the plant's model.

The plant's model sought after might be generally written according to relation (1), in which it has been assumed, that the output signal value in *k* step depends both on the output signal in the previous steps, on the input signal *u(k)* accompanied by a digital delay, and the interference modeled as white noise:

$$y(k) = z^{-d}\frac{B(z^{-1})}{A(z^{-1})}u(k) + \frac{C(z^{-1})}{A(z^{-1})}\upsilon(k), \tag{1}$$

where:
y(k) – the input signal in the *k* step,
u(k) – the output signal in the *k* step,
d – digital delay,

$G_P(z^{-1}) = \dfrac{B(z^{-1})}{A(z^{-1})}$ - control chain transmittance (the object model)

$H(z^{-1}) = \dfrac{C(z^{-1})}{A(z^{-1})}$ - interference chain transmittance.

The regulation object model presented above is known in the literature under the name ARMAX [9]. In the engineering practice, however, its simplification is commonly used – an ARX model, in which it is assumed, that the polynomial $C(z^{-1}) = 1$. The aim of the identification is setting an object model in the following form:

$$G_P(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{b_0 + b_1 z^{-1} + \ldots + b_{nB} z^{-nB}}{1 + a_1 z^{-1} + \ldots + a_{nA} z^{-nA}} \tag{2}$$

The above relation can be presented as a linear form of a product of measurement data vector $\varphi^T(k-1)$ and parameters vector of a model θ :

$$y(k) = \varphi^T(k-1)\theta + \upsilon(k) \tag{3}$$

where:

$\varphi^T(k-1) = [-y(k-1), -y(k-2), \ldots, -y(k-nA), u(k-d), u(k-d-1), \ldots, u(k-d-nB)]$,

$\theta = [a_1, \ldots, a_{nA}, b_0, \ldots, b_{nB}]^T$,

nA, *nB* – degrees of polynomials defining a model's structure.

The parameters' vector sought after can be calculated on the basis of a minimization criterion of a mean square error [9]:

$$\hat{\boldsymbol{\theta}} = Arg\min\left(\sum_{k=1}^{N}\left[y(k) - \varphi^T(k-1)\hat{\boldsymbol{\theta}}(k)\right]^2\right) \tag{4}$$

In the designed software a recursion algorithm with regularization has been implemented, proposed in the study [8] and described by means of the formulas below:

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \boldsymbol{L}(k)\varepsilon(k)$$

$$\boldsymbol{L}(k) = \frac{\boldsymbol{P}(k-1)\boldsymbol{\varphi}(k)}{1 + \boldsymbol{\varphi}^T(k)\boldsymbol{P}(k-1)\boldsymbol{\varphi}(k)}$$

$$\varepsilon(k) = y(k) - \hat{\boldsymbol{\theta}}^T(k-1)\boldsymbol{\varphi}(k) \tag{5}$$

$$\boldsymbol{P}(k) = q\boldsymbol{\Lambda}(k) + r\boldsymbol{I}$$

$$\boldsymbol{\Lambda}(k) = \boldsymbol{P}(k-1) - \frac{\boldsymbol{P}(k-1)\boldsymbol{\varphi}(k)\boldsymbol{\varphi}^T(k)\boldsymbol{P}(k-1)}{1 + \boldsymbol{\varphi}^T(k)\boldsymbol{P}(k-1)\boldsymbol{\varphi}(k)}$$

$$q = \frac{\gamma_{\max} - \gamma_{\min}}{\gamma_{\max}}$$

$$r = \gamma_{\min}$$

where:

$\gamma_{\min}, \gamma_{\max}$ - mean regularization parameters.

3.3. The regulator's settings update

The considered adaptive control algorithm uses the previously set in the identification process (in *on-line* mode) the plant model's parameters values in order to calculate new regulator's settings. On of the methods commonly used in setting formulas describing the relations between the object model and the regulator's parameters is the full state feedback method [1]. This technique strives to the transmittance poles' dislocation, so that the closed-loop system would be stable and meet all control targets.

$$G_W = \frac{Y(z^{-1})}{W(z^{-1})} = \frac{B(z^{-1})Q(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})} \tag{6}$$

Assuming, that the regulator's transmittance is described by the relation below:

$$G_R(z^{-1}) = \frac{Q(z^{-1})}{P(z^{-1})} = \frac{q_0 + q_1 z^{-1} + \ldots + q_{nQ} z^{-nQ}}{p_0 + p_1 z^{-1} + \ldots + p_{nP} z^{-nP}} \quad , \tag{7}$$

the formulas sought after and presenting one of the methods of calculation new regulator's settings, might be defined by means of solving the following Diophantine equation [5]:

$$A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1}) = D(z^{-1}) \tag{8}$$

where:

$$D(z^{-1}) = \sum_{i=0}^{nd} d_i z^{-i} = d_0 + \sum_{i=1}^{nd} d_i z^{-i} \tag{9}$$

stands for a polynomial describing the set locations of the closed-loop system poles. In the given tests one has assumed PID regulator structure and ARX object model of 2nd order and the following transmittances, respectively:

$$G_R = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2}}{1 + p_1 z^{-1}} \tag{10}$$

$$G_P = \frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}} \tag{11}$$

Thus, the following parameter values have been assumed: $nQ = 2$, $nP = 1$, $nA = 2$, $nB = 1$, $d = 1$, $p_0 = 1$, which ensure meeting all identification condition of the regulation object in the closed-loop system.

Taking into consideration the above assumptions, the diophantine equation leads to a system of linear equations:

$$\begin{bmatrix} 1 & b_1 & 0 & 0 \\ a_1 & b_2 & b_1 & 0 \\ a_2 & 0 & b_2 & b_1 \\ 0 & 0 & 0 & b_2 \end{bmatrix} \begin{bmatrix} p_1 \\ q_0 \\ q_1 \\ q2 \end{bmatrix} = \begin{bmatrix} d_1 - a_1 \\ d_2 - a_2 \\ d_3 \\ d_4 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{12}$$

Solving the system, one may obtain the formulas presenting the adaptive regulator's settings in the forms below [6]:

$$p_1 = \frac{b_1^2(b_1 x_4 - b_2 x_3) + b_2^2(b_1 x_2 - b_2 x_1)}{b_2(a_1 b_1 b_2 - a_2 b_1^2 - b_2^2)} \tag{13}$$

$$q_0 = \frac{b_2^2(a_1 x_1 - x_2) + b_1 b_2(x_3 - a_2 x_1) - b_1^2 x_4}{b_2(a_1 b_1 b_2 - a_2 b_1^2 - b_2^2)} \tag{14}$$

$$q_1 = \frac{b_2^2(a_2x_1 - x_3) + b_1b_2(a_1x_3 - a_2x_2 + x_4) - a_1b_1^2x_4}{b_2(a_1b_1b_2 - a_2b_1^2 - b_2^2)}$$

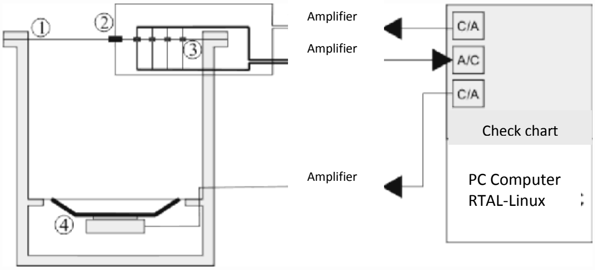
$$q_2 = \frac{x_4}{b_2} \qquad (15)$$

4. Circular plate active vibration reduction

One of the aims of the works is to analyze the possibilities of employment the adaptive control into thin surface systems' vibration reduction. The components' vibrations, being the elements of industrial machines, cars, ships, airplanes, civil structures, home appliances, etc., is in many cases an unwanted phenomenon, elimination of which should be performed in the designing or operation phase.

4.1. RTAI-Linux based vibration reduction system

As a part of the works, an experimental mechatronical system designed for circular plate vibration reduction, presented on figure 3. Designing the system, a series of aspects was taken into consideration, which may influence its potential employment possibilities in industrial solutions, e.g. slight impact of additional measurement and automation elements on its basic tasks realization, high reliability and low production and operation costs.



a) Functional diagram: 1 – circular plate, 2 – piezoceramic actuators, 3 – strain gauges, 4 - speaker

b) Real workplace

Fig. 3. Circular plate vibration reduction system

An object consisting of a cast-iron cylinder of the following parameters: 0,8 m height, 0,5 m diameter, 120 kg weight, is included in the workplace. Inside the cylinder, 0,5 m from the upper edge a main element of the vibration forcing system – a subwoofer. The tested plate was located between two rings: lower, being a part of the cylinder's body, and upper, pressing the plate by means of four pneumatic actuators. The designed pneumatic pressure system enables obtaining a balanced load on the plate's perimeter and meeting the boundary condition (consolidation). At the same time, there is a possibility of the pressure force smooth regulation through nitrogen pressure change, supplying the pneumatic circuit.

In the mechatronical system 4 pairs of tensometric detectors were used as measurement chain elements, stuck into the plate's radius on both its sides (in order to increase its sensitivity). A voltage signal, proportional to the vibration amplitude, is filtered, strengthened and transformed into a digital form by means of an A/C transducer (data acquisition card). A pair of piezoceramic, disc-shaped actuators, stuck on both sides of the plate, was used in its central point as performance chain elements. The localization was chosen on the basis of theoretical calculations presented in the study [4]. The system operation is supervised by a control unit – a PC computer with a real-time RTAI-Linux system. Such a solution was chosen due to its specific characteristics:

- performing tasks with deterministic response time – in the worked out system some of its functions associated with operation has to be realized, keeping a constant, imposed response time. It is possible due to the employment of the real-time system. Applying of such a solution allows to a considerable increase of the control algorithm speed
- availability and software low cost – RTAI library, supplementing the standard Linux system with additional modules realizing the real-time system functions, is distributed on the basis of GNU license, thus it may be used free of charge in industrial solutions as well. Numerous tools, supporting the control algorithm's designing and *hardware in the loop* prototyping, have been developed. They enable quick testing of new software (RTAI-Lab library)
- implementation on different computing platforms – RTAI-Linux system supports the following solutions: 32- and 64-bit processors (x86 and x86_64), PowerPC, ARM microcontrollers (StrongARM; ARM7: clps711x-family, Cirrus Logic EP7xxx, CS89712, PXA25x) and Motorola microprocessors (m68k). It enables further implementation of the created software on a whole series of software, depending on particular needs and platforms employed.

A software implementing the given adaptive control algorithm has been worked out on the basis of this solution. Model results of system operation are presented in the further part of this chapter.

4.2. Test results

As part of the works, numerous simulation and experimental tests have been performed with the use of the workplace and the software. On the basis of the measured values of the input (set by means of PZT elements) and output signal (measured by the tensometric detectors), tests of the proposed identification algorithm have been conducted. They have been performed by means of a so-called S-function (Matlab/Simulink), presented in the figure below:

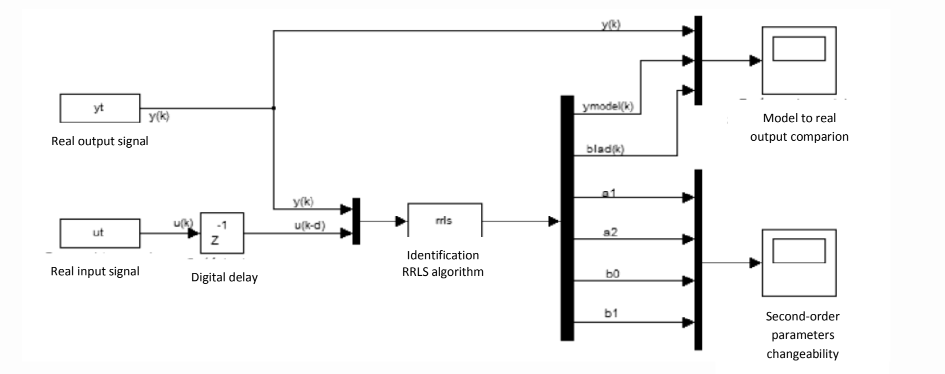
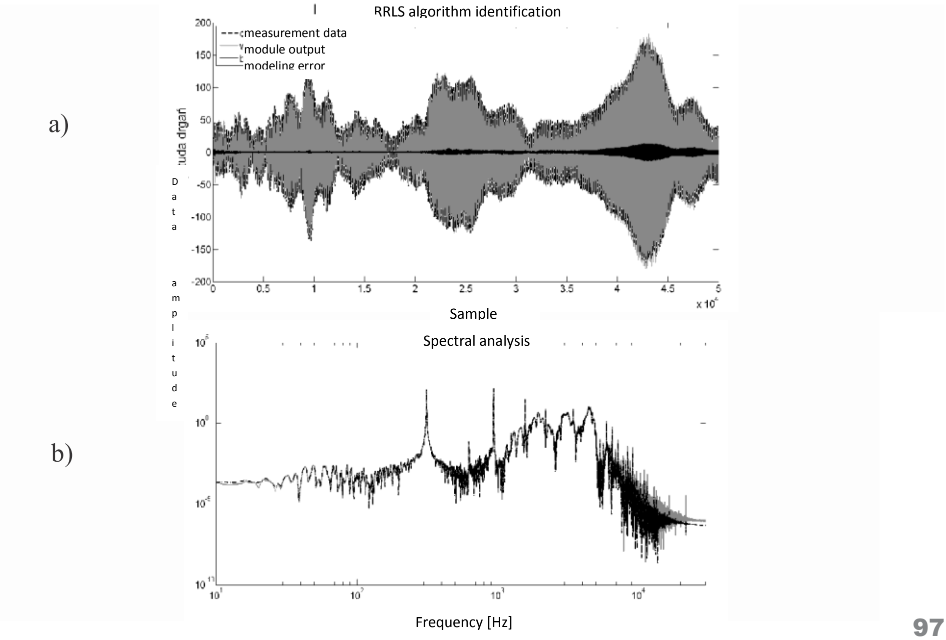
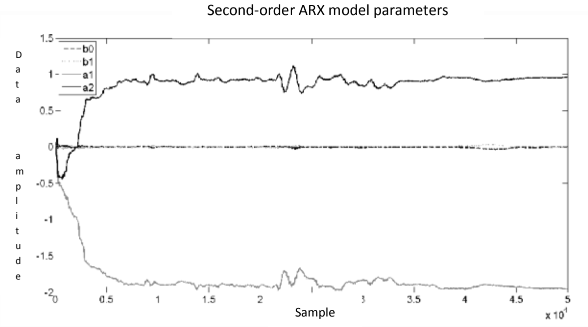


Fig. 4. RRLS algorithm – SIMULINK model

The given S-function takes the ARX model order as a set parameter and on the basis of two parameters sets the object model parameters, as well as the output signal value and the modelling error. It has been assumed on figure 4, that the model order amounts to 2, so the model consists of 4 parameters. On figure 5, on the other hand, model simulation results for real measurement data are presented. A signal *chirp* has been taken as the input signal (200-400 Hz frequency).



c)

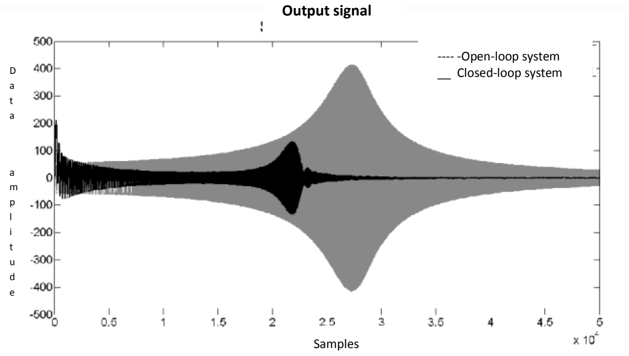


Second-order ARX model parameters

Fig. 5. second-order ARX model identification

On the basis of diagrams a) and b) one may observe that the identification algorithm employed in forming of the S-function possesses high level of precision, both in case of time and frequency. The ARX model output signal coincides with the real output signal in the whole range taken into consideration, despite the fact that it is of the second-order only. It is possible only due to its high sampling rate (10 kHz), exceeding the given signal frequency range 10 times. On the c) diagram the course of the object model parameters' changes is presented, for the regulations $\gamma_{\min} = 0.001$, $\gamma_{\max} = 1000$. As can be seen, the above-mentioned parameters' values cause slight changes in the ***P*** matrix in the RRLS algorithm, yet they have a significant impact on the increase of its stability.

The next diagram, shown as figure 6, presents the route of the output signal of the plant for closed and open system.



Output signal

Fig. 6. Response of the system within the open and closed loop for *chirp* signal (100-500 Hz).

The second-order ARX model and the PID adaptive regulator for the given circular plate vibration reduction was chosen as part of the tests. The conducted experiments show that by means of the above-mentioned method, a proper identification of the regulation object model and adaptive tuning of the regulator parameters are possible. As can be seen, the employment of the adaptive regulator causes a considerable reduction of the plate's vibrations.

5. Conclusion

The mechatronical system structure realizing the task coping with the plate's active vibration reduction, performed by means of the adaptive control method, has been presented in this chapter. The proposed approach may be extended by the notions of vibration elimination of plates of different shapes that often are: industrial machines, cars, ships, airplanes, civil constructions elements (various barriers), etc. As has been proved, the vibration phenomenon may have a vital, negative effect both on functioning efficiency of given structures (precision, wear and tear), and on the service personnel working comfort, as well as the surroundings acoustics. Therefore, the vibration reduction is an important issue that should be taken into account during the designing and operation stages of such systems.

Tests performed with the use of the software implementing the adaptive, proposed algorithm indicate high vibration reduction reliability of this method. Low construction and operation cost are obtained by standard software solutions and minimization of operational services, as well as by its properties associated with adaptation to changing machine operation conditions, significantly influencing the potential extension of industrial devices' employment area.

Summary

The devices structural elements vibrations may have a significant, negative impact on their operation because they cause the efficiency decrease, loss of strength and the operator's working conditions deterioration (noise). In this chapter the mechatronical system structure has been presented. Its task is to reduce the plate's vibrations, very often being components of industrial machines, cars, ships, airplanes, civil constructions, home appliances, etc. In the proposed solution, one of the so-called active methods, the adaptive control algorithm has been used. Its essence is associated with automatic regulator's settings during the control process, based on the signal values measured at a particular moment. Such activity enables broad employment of the given system in the industry, especially when the device's working conditions, in which it would be used, are subjected to continuous changes. Application of the above methods considerably reduces costs of the operator's work what would have to be done with the aim of redesigning a classic regulator of stable settings.

In the proposed system, a PC computer acts as a control unit. It is fit with properly selected check charts and controlled by a real-time RTAI-Linux operation system. Numerous simulation tests with the use of MATLAB/SIMULINK have been conducted as part of the researches. What is more, using the advantages of RTAI library, the software implementing the chosen adaptive control algorithm has been worked out.

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Application of parallel algorithms in the problem of audio and video restoration on the basic of the LMS algorithm in mechatronics

Maciej Walczyński*

Summary

This paper describes a concept of parallelization of filter adaptation algorithms for digital denoising problems for audio and video signals. For proposed approach the fast parallel algorithm based on LMS filter and implemented in nVidia CUDA environment was presented.

Keywords: parallel computing, digital signal processing, signal denoising.

1. Introduction

Denoising of audio and video signals is a perfect example of wide range of issues, in which the adaptive filtration has been employed [5, 6, 9]. The problem of interferences may occur for instance in the case of audiovisual recordings, being an evidence in judicial proceedings. The signal deformed by such noises may also appear during the ECG, for instance in form of an electric hum [3, 8]. Deformed by the interference may be a telephone conversation in moving car, too. As can be seen, the denoising issue is an essential problem, not only theoretical, but also the application one. It should be observed that the notion of noise has a broader meaning and covers every interfering signal, for example a harmonic signal of interference nature, white noise, pink noise, etc. The adaptive filtration as a denoising method possesses an important feature, differentiating it from the other ones. Namely, the knowledge of the signal and the interfering signal is not required a priori.

The employment of algorithms to the images and sounds denoising problem is very broad in the still „young" mechatronics domain. An example illustrating the algorithm's application in mechatronical denoising is associated with the initial automatic classification system. Such analysis may take place as soon as in the ending production

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stage, when the products are still on the assembly line. Such system, equipped with a camera recording parameters of a pig iron, may be used in the metallurgy with parametrization and classification processes. One of the main elements of the system may be a noise elimination system that would improve the video parameters, because of which the product's classification would be more adequate.

Another issue, in which the parallel algorithms of denoising can be employed, are park assist systems, line assistance or traffic sign recognition system. These systems are to support the driver, who in the era of increasing street traffic volume must perceive an increased amount of stimuli and analyze them. Some of them use recordings from a camera located inside a car. This image is processed, parametrized, classified and on the basis of these three procedures actions are performed. In the Ford TSR system (TrafficSignRecognition) a car's vicinity is recorded by a video camera. From this image the data associated with road signs before a car are taken out. Then, a visual information appears in front of a driver, on a control panel screen. As time goes by, the automobile companies use more elaborated and at the same time more complex systems supporting the driver. The parallel denoising algorithms can be found even in such systems.

2. An outline of the problem

A model situation that help illustrate a rule, which is a base for the LMS algorithm operations, might be shown in the following way: There is a telephone conversation in a moving car. The faster this car goes, the bigger is the noise level of the engine, air whirlwinds on the bodywork, etc. The conversation's comfort is interfered by these obstructions. As a result of this, their elimination is desired.

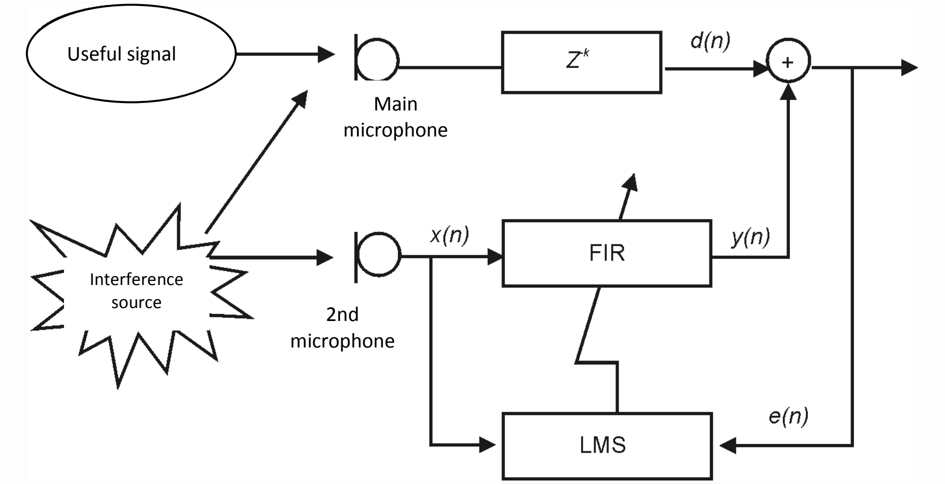


Fig. 1. A denoising adaptive device schema

The proposed algorithm works on the basis of two signals. The first one *d(n)* comes from the microphone installed inside a car and except a useful voice signal *s(n)*, it contains unwanted interferences $x_1(n)$ (for instance working engine noise). The second one $x(n)$ is collected by means of another microphone located some distance away from the first one. Such signal does not possess any information connected with the driver's conversation, but does possess information about the interfering signal characteristics. Obstructions coming from both microphones may differ, as far as amplitude, phase and other parameters are concerned, but a kind of correlation exists among them. It allows to use the adaptive filtration method in interference elimination. The adaptive filter changes the signal's $x(n)$ parameters (amplitude, phase displacement) in such a way, that the changed signal $y(n)=H(x(n))= \quad (n)$ is adapted to the $x_1(n)$ signal by means of the error signal $e(n)$ minimization. The output signal contains a denoised version of driver's voice.

3. LMS sequential algorithm

The LMS (Least Mean Square) filter, proposed for the first time in the 60. by Widrow and Hoff, is probably the most commonly used adaptive filter. Its characteristics are relative implementation simplicity (in the sequential version) and stability [2, 7]. The LMS filter is an example of a gradient adaptive filter. In this case it is assumed, that the change $\Delta h(n)$ of a vector $h(n)$ possessing the filter's coefficients, should be in every moment proportional to the function gradient vector:

$$\frac{\mathbf{h}(n+1)=\mathbf{h}(n)+\Delta\mathbf{h}(n)=\mathbf{h}(n)-\frac{1}{2}\mu(n)\,\mathbf{W}(n)\big(\partial J(\mathbf{h}(n))\big)}{\partial\mathbf{h}(n)} \tag{1}$$

where $\mu(n)$ is a scalar scale coefficient which influences the filter's modification speed. On the other hand, the $W(\mathrm{n})$ factor is a matrix destined to improve the algorithm's convergence.

As far as the LMS filters are concerned, an error signal momentary value minimization is assumed here. This criterion can be presented in the equation below:

$$J=e^2(n). \tag{2}$$

A derivative of this expression, regarding changes of the filter's coefficients, is presented with the use of the following formula, where M stands for the filter's order.

$$.\frac{\partial J(\mathbf{h}(n))}{\partial\mathbf{h}(n)}=\left[\frac{\partial e^2}{\partial\mathbf{h}_0(n)},\frac{\partial e^2}{\partial\mathbf{h}_1(n)},\dots,\frac{\partial e^2}{\partial\mathbf{h}_M(n)}\right]^T, \tag{3}$$

Furthermore, the partial derivative value towards k coefficient of the filter is shown below:

$$\frac{\partial e^2(n)}{\partial h_k(n)}=2e(n)\frac{\partial e(n)}{\partial h_k(n)}=2e(n)\frac{\partial(d(n)-\Sigma_{K=0}^{M}(h_k x(n-k)}{\partial h_k(n)}=2e(n)x(n-k), \tag{4}$$

where expression$\Sigma_{K=0}^{M}(h_k x(n-k)$ is the referenced signal's estimator.

In case of the LMS filters it is assumed, that the matrix $W(\mathrm{n})$ is a unit diagonal matrix.

Finally, the equation (1), describing the adaptation process of the filter's coefficients takes the following form:

$$\mathbf{h}(n+1) = \mathbf{h}(n) + \mu(n)e(n)\mathbf{x}(n) \tag{5}$$

Even in the simplest of examples, independence of the $\mu(\mathrm{n})$ factor to time is also assumed. In such situation, the equation (5) is modified in the following way:

$$\mathbf{h}(n+1) = \mathbf{h}(n) + \mu e(n)e(n)\mathbf{x}(n). \tag{6}$$

4. Parallel computing

In the recent years it has been observed that computers' speed, understood as clock rate, does not increase. It means that the technology reached a peculiar barrier. One of solutions of this issue is employment of more efficient cooling processes, for instance with the use of liquid nitrogen. Yet, such approach does not have any economic justification. Another solution is multi-core processors application. Dual- and quad-core processors are nothing unusual nowadays.

In 2007, Intel implemented an 80-core processor. The approach based on the core amount increase has been one of the most popular methods lately. It deals with computer systems efficiency increasing, using parallel architecture. According to the Flynn's taxonomy [4], the following computer architectures can be divided:

- SISD (Single Instruction Single Data),
- SIMD (Single Instruction Multiple Data),
- MISD (Multiple Instruction Single Data),
- MIMD (Multiple Instruction Multiple Data).

Metric spaces, used in both parallel and sequential algorithms, consist of:

- computing time,
- speed-up,
- effectiveness.

The parallel algorithm computing time is required to be shorter than the sequential algorithm computing time.

The parallel algorithm computing time can be divided into several parts. The first element is T_s sequential code part run-time. it results from a simple fact that not every operation can be paralleled and this operation's parallelization is associated with longer operation time. The next element of total computing time is T_p algorithm's parallelized elements run-time. Other components having an impact on the algorithm's run-time are T_c communication time (both between thread and between CPU and GPU) and T_i idle time.

In general, the final run-time of the parallel algorithm can be expressed in the following equation:

$$T = T_s + T_p + T_c + T_i \tag{7}$$

Another metric space determining the algorithm's efficiency is the absolute speed-up. This parameter is expressed below:

$$S^* = \frac{T_s}{T_p}, \tag{8}$$

where T_s is the run-time of the fastest sequential algorithm solving a given issue and T_p is the parallel algorithm run-time.

The general speed-up (in the literature also called „orthodox speed-up", see [1]) expresses the ratio of the parallel algorithm run-time on one processor to the parallel algorithm run-time on *p* processors. It is shown in the following equation:

$$S = \frac{T_1}{T_p}, \tag{9}$$

where T_1 is the algorithm run-time on one processor and T_p is the algorithm run-time on *p* processors.

In practice, the general speed-up is used more common than the absolute speed-up. It is also more practical (the algorithms implemented on the same processors are compared).

Around 2000 a new computing technology began to be carried out. It was associated with general computing using by graphic card's processors. In 2006 nVidia presented a CUDA technology enabling programming of GPU systems in C programming language. SIMD architecture is employed in the CUDA technology approach. It is based on multiple processors operation, solving the same task on the basis of various data. Such approach allows to obtain higher efficiency, but requires a different paradigm of programming than in the case of the sequential algorithms.

In 2011 nVidia and BMW announced the signing of the agreement. It deals with cooperation based on nVidia GPU systems delivery and their assembly in management and navigation systems of BMW cars [10].

An increasing number of car marks is being equipped with various, often very advanced driver supporting programs. Such systems require real-time operation, which in turn requires high computing power and are associated with automatic sign recognition, line assistant and active noise reduction systems. Low error susceptibility is also required because in numerous situations their proper operation might decide over the passengers' safety. One of the elements possessing negative impact on such systems are sensor and measuring device interferences (such as camera and microphone). In the present study a new approach of denoising is presented. It deals with the employment of the parallelized LMS algorithm that may be used in eliminating interferences from audio and video signals.

5. The parallel LMS algorithm

The parallel LMS algorithm formation requires an effective employment of the technological possibilities. The main issue is associated with optimal use of various memory types. The CUDA technology offers 6 memory types:

- register – non-addressable memory for storaging variables,
- local memory – local memory available only during performing a so-called kernel (e.g. a program running on GPU),
- shared memory – fast shared memory for all thread in a block,
- global,
- texture,
- constant.

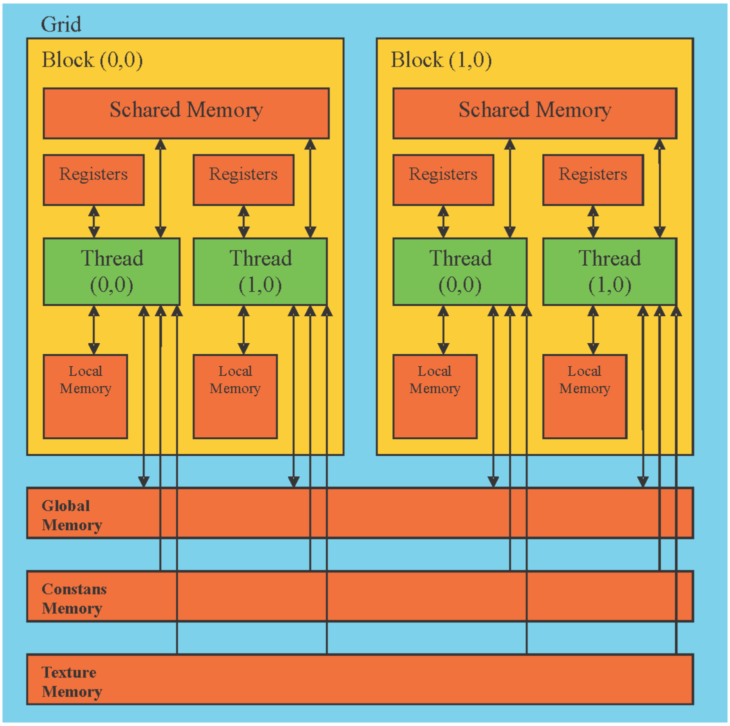
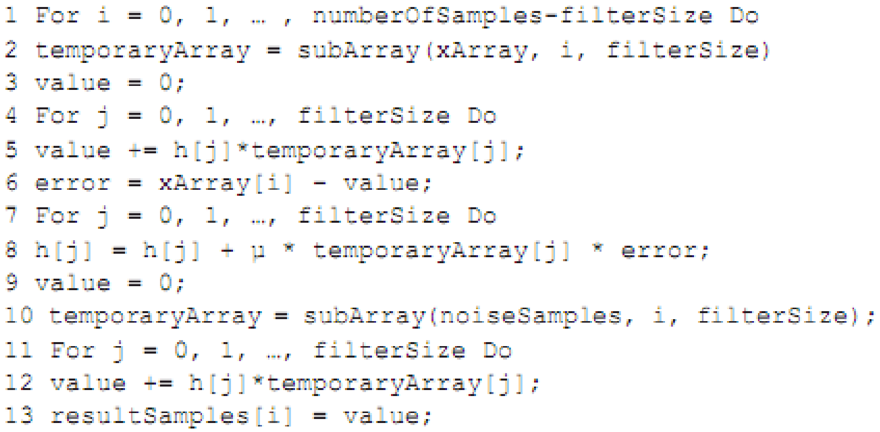


Fig. 2. A memory model used in the nVidia Cuda technology

Optimization requires the above-mentioned memory types, especially buffered memories on L1/L2 level (for instance shared memories).

Moreover, minimization of connection number between CPU and GPU is also essential due to PCI-Express small throughput.

The effectively implemented algorithms using the CUDA technology should not contain recursion. The program should be organized not around the algorithm, but around the data, while the GPU functions (so-called kernels) should contain the highest number of mathematical instructions possible.



```
For i = 0, 1, … , numberOfSamples-filterSize Do
    temporaryArray = subArray(xArray, i, filterSize)
    value = 0;
    For j = 0, 1, …, filterSize Do
        value += h[j]*temporaryArray[j];
    error = xArray[i] - value;
    For j = 0, 1, …, filterSize Do
        h[j] = h[j] + µ * temporaryArray[j] * error;
    value = 0;
    temporaryArray = subArray(noiseSamples, i, filterSize);
    For j = 0, 1, …, filterSize Do
        value += h[j]*temporaryArray[j];
    resultSamples[i] = value;
```

Fig. 3. The sequentional LMS algorithm pseudocode

The implementation of the LMS adaptive filter parallel version was based on the algorithm’s components isolation and parallelization. In the presented approach, the signal was divided into several components. For every one of them the parallel working LMS filter was switched on. Each thread is responsible for the algorithm’s working out in the divided signal fragment. What is more, each thread possesses its own, independent LMS filter. Such implemented algorithm was used in audio signals denoising. The filtration effect using the parallel LMS filter for a sinuous signal denoising is presented in the figure below.

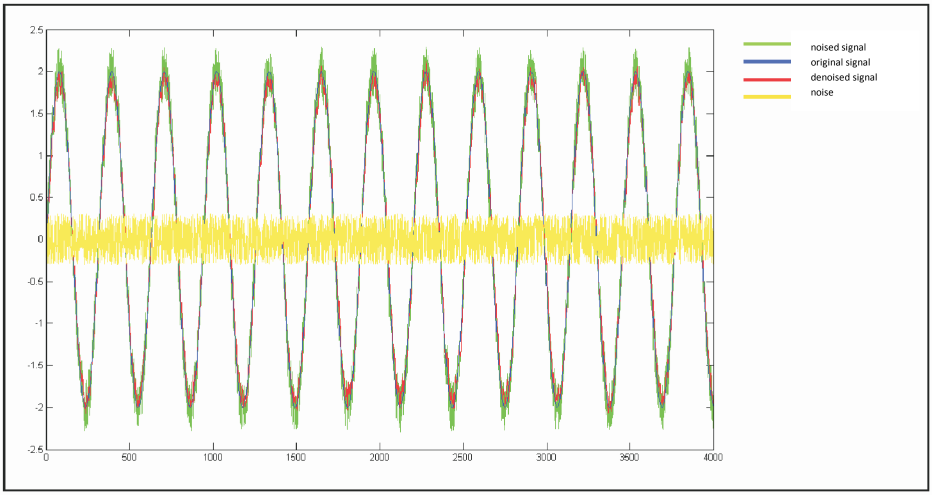


Fig. 4. The parallel LMS filter operations on a noised, sinuous signal

6. Computing experiments

The parallel LMS algorithm efficiency was tested on the basis of a audio file containing noised voice. The denoising signals system were conducted for a sequentional algorithm on nVidia Tesla S2050 and Tesla C870 cards. Both cards' parameters are presented in the table below:

Tab.1. nVidia Tesla S2050 and Tesla C870 cards' parameters

	nVidiaTestla C870	**nVidiaTestla S2050**
Number of processors	128	448
Computing power (single precision/double precision)	n.a./500	1030/515
Memory	1,5 GB	6 GB
Memory throughput	76.8 GBps	150 GBps

In Tables 2 and 3 averaged times of hundred-time parallel algorithm performances for various number of threads and grid dimensions (e.g. group of blocks processed in different microprocessors) are presented. Times required for memory allocation, data copying to a card, computings, data copying from GPU card are detailed.

Tab. 2. nVidia Tesla S2050 computing times

Thread number	**Grid dimension**	**Memory allocation time [ms]**	**Copying data to card time[ms]**	**Computing time [ms]**	**Copying from device time [ms]**	**Total time [ms]**
1	1	1,76	95,12	53471,45	48,44	53616,70
32	1	1,83	101,94	12335,51	50,87	12490,12
256	1	1,62	94,30	3208,68	44,67	3349,28
512	1	1,69	91,03	4898,11	46,17	5037,00
1024	1	1,90	102,80	6700,62	53,22	6858,52
256	100	1,68	91,50	573,12	46,84	713,14

The shortest algorithm run-time was obtained for 256-thread program with grid dimension of 1000, running on nVidia Tesla S2050 card. Total run-time amounted to 655,89 milliseconds. The memory allocation time is 1,67 ms and it reaches up to 2,5 per mille of total time. Averaged total data copying time to card in this configuration comes to 89,82 milliseconds, e.g. 13,7% of total time. The longest time is taken by the calculations, performance of which took nearly 518 ms, e.g. around 79% of the task total time. Copying data to card time made up over 7% of total time.

Tab. 3. nVidia Tesla C870 computing times

Thread number	Grid dimensions	Memory allocation time [ms]	Copying data to card time [ms]	Computing time [ms]	Copying from device time [ms]	Total time [ms]
1	1	15,01	331,96	164646,41	180,91	165174,48
1	32	15,47	346,82	5597,71	200,61	6160,61
32	1	13,66	337,21	7700,86	177,40	8229,15
32	256	14,13	311,43	3047,44	180,95	3553,95
1	256	14,87	333,79	2840,71	191,36	3380,75
256	1	15,45	344,94	4976,86	203,76	5541,03
256	10	10,06	283,34	5542,39	151,20	5987,09
256	200	14,16	316,31	880,44	182,88	1393,79

Tables 4 and 5 present the percentage share of memory allocation operations, copying data to card, computing and copying data from card during the algorithm operation for different configurations of thread number and grid dimensions.

Tab. 4. Percntage share of memory allocation operations, copying data to card, computing and copying data from card during the algorithm operation on nVidia Tesla S2050

Thread number	Grid dimensions	Memory allocation [%]	Copying data to card [%]	Computings [%]	Copying data from card [%]
1	1	0,003	0,177	99,729	0,090
32	1	0,015	0,816	98,762	0,407
256	1	0,048	2,816	95,802	1,334
512	1	0,034	1,807	97,243	0,917
1024	1	0,028	1,499	97,698	0,776
256	100	0,236	12,831	80,366	6,568
256	1000	0,255	13,694	78,966	7,084

The relative speedup for this algorithm, running on 256-thread program of grid dimension 1000, on nVidia Tesla S2050 card, amounts to:

$$S = \frac{\mathbf{T_1}}{\mathbf{T_p}} = \frac{\mathbf{53616{,}70[ms]}}{\mathbf{655{,}89[ms]}} = \mathbf{81{,}71}$$

Tab. 5. Percntage share of memory allocation operations, copying data to card, computing and copying data from card during the algorithm operation on nVidia Tesla C870

Thread number	**Grid dimensions**	**Memory allocation [%]**	**Copying data to card [%]**	**Computings [%]**	**Copying data from card [%]**
1	1	0,009	0,201	99,680	0,110
1	32	0,251	5,630	90,863	3,256
32	1	0,166	4,098	93,580	2,156
32	256	0,398	8,763	85,748	5,092
1	256	0,440	9,873	84,026	5,660
256	1	0,279	6,225	89,818	3,677
256	10	0,168	4,733	92,572	2,525
256	200	1,016	22,694	63,169	13,121

The greatest speedup for nVidia Tesla C870 amounted to 118,51 for 256-thread program and grid dimension 200.

Speedups for both cards and specific grid dimension and thread number configurations are presented in Table 6.

Tab. 6. Speedup values for nVidia Tesla S2050 and nVidia Tesla C870, depending on thread number and grid dimensions

nVidia Tesla S2050			**nVidia Tesla C870**		
Thread number	Grid dimension	Speedup	Thread number	Grid dimension	Speedup
32	1	4,29	1	32	26,81
256	1	16,01	32	1	20,07
512	1	10,64	32	256	46,48
1024	1	7,82	1	256	48,86
256	100	75,18	256	1	29,81
256	1000	81,75	256	10	27,59
-	-		256	200	118,51

7. Conclusion

The parallel algorithm designed for denoising has been presented in this study. Good denoising effects and high speedup values have been obtained during computing experiments. It is confirmed by the fact that the above-presented method is a lot faster than the sequential approach. The possibilities of both parallelization of the other adaptive filtration LMS and RLS algorithms, and independent operation of the LMS parallel algorithm in subbands.

The employment range of algorithms eliminating various audio and video interferences is very broad. The use of the parallel algorithms implemented into nVidia CUDA concurrent computing environment, or on FPGA systems in videoconference systems should improve the audio-video quality by means of more effective denoising and acoustic echo elimination. It would have a significant impact on work comfort and efficiency. It should be noted that many large companies use videoconferences as a means of employee-based communication working in different branches, which more than once are located in miscellaneous countries or continents. Another employment of the applications associated with parallel denoising methods is an intelligent transportation system. This solution is based on the employment of a balance built into the road. Such balances enable a car's curb weight estimation. If the weight exceeds permissible value, the system will analyze a video recording and identify the vehicle by means of appropriate image identification software linked with a video camera. In case of bad weather (for example rain- or snowfall), the video image might have some interferences. The parallel denoising algorithms should enable quick vehicle identification and transferring of proper data to database in order to inform appropriate road services.

Summary

A concept of the adaptive filtration algorithms parallelization for digital acoustic and visual signals denoising issues has been presented in this paper. For the proposed approach, both an algorithm based on the parallelized LMS filter, implemented into nVidia CUDA concurrent computing environment, has been shown, and GPU computing results have been produced.

Keywords: signals denoising, parallel computing, adaptive filtration.

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Simulation of complex dynamic systems

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Summary

The paper presents design of original software for the simulation of complex dynamical systems intended to work in real-time mode. The module has a high accuracy of calculations and is dedicated to mechatronical systems with complex structure consisting of moving parts connected by joints. Used in the module, the ABA algorithm, of the computational complexity O(N), allows to perform complex simulations in real time.

Keywords: computer simulation, articulated body algorithm, robotics, virtual mechatronical analysis.

1. Introduction

Simulation is a process dealing with approximate reconstruction of a phenomenon or behavior of a given object by means of its model. It is widely used in such fields, as:

- science,
- medicine (modern diagnostics, internal organs modeling),
- industry (simulators, training simulators, SCADA, medicine synthesis),
- economics and business,
- entertainment (complex games),

creating a class of specialist, dedicated software.

The study presents a program component worked out by the authors – a “physical engine”, which is a part of a simulator – of an original software designed for complex dynamical system simulations, working in real-time and characterized by high-precision computing. The cause of the works on the own version of the “physical engine” were results of tests performed for several chosen mechatronical systems of

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high complexity, with the use of three main libraries: "Havok", "Bullet" and "PhysX". The tests revealed their deficiencies and operation differences. They do not meet a main assumption of scientific simulation, high computing precision (maybe except for "Bullet"), and what is more, they cannot solve some of the properly configured systems (for instance associated with body collisions of high empty weight ratio.

The second factor for construction of the own „engine" is a possibility of employing the most modern algorithms (accurate and characterized by computational complexity (O(N)) dealing with a simple and inverse dynamic task and associated with precise integration algorithms and component programming technique. It is assumed that the given engine in a time unit of 1/60 s will allow to solve a system consisting of 300 articulated rigid bodies on a modern PC computer equipped with a graphic card of 512 CUDA units (NVIDIA) or its equivalent (AMD-ATI). Such efficiency will enable the working out of a new generation of surgery robot simulators, designed for virtual surgery trainings (scientific simulation) or will allow to employ them in the Polish Serious video games (of high-quality real animation). It should be pointed out that the "engine-physics" is one of the essential simulator's components. Its structure is presented in figure 1.

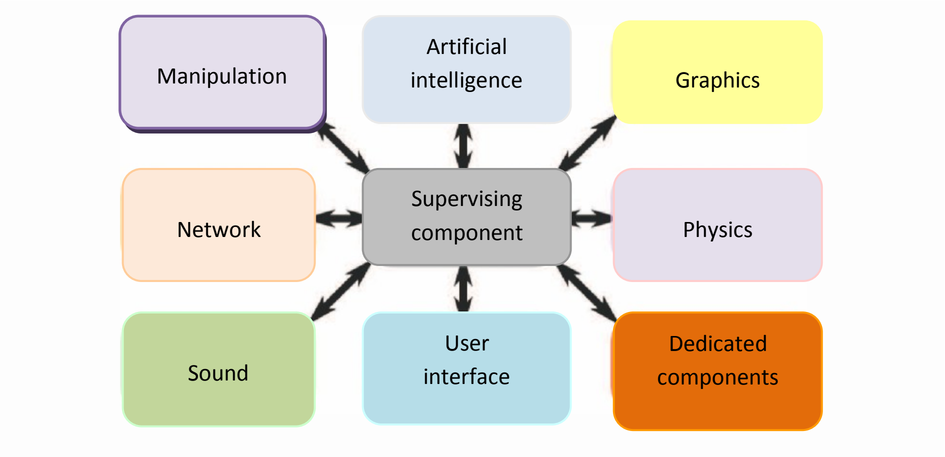

Fig. 1. – Simulator's structure – components system

Each of the components presented on Fig. 1 might be considered as a program thread characterized by individual update frequency, having an equivalent in form of real-time systems' sampling time. Typical main programming blocks update frequency values are gathered in Table 1. The "physics" component may contain several internal threads operating on frequencies ranging from 10 Hz up to 1 MHz, what indicates on programming time relations degree. The simulator is then a system of parallel processes of different frequencies, synchronized by data exchange operations.

Tab. 1. Typical component frequency values

Component	**Graphics**	**Manipulation**	**Sound**	**Network**	**AI interface**
Update frequency [Hz]	60-100	10-1000	44 000	1000	100

Big difference between the lower and upper frequency range of the “physics” component arises from the fact that in a complex system objects of various motion dynamics cooperate or coexist (for instance micro- and macro machines/sub-assemblies. Moreover, the “physics” component is a point of reference for the body collision model and more complex collision outcome model. The issues listed above are hardly unified and are at standard forming stage, possible to be employed in simulators/training simulators or “Serious games” applications.

2. Dynamics model – ABA algorithm

One of the basic tasks of the physical library is rigid bodies system dynamics which might be connected by means of joints and might be subjected to any forces. The physics model should in particular solve two computing issues:

(i) simple dynamics – deals with system speedup setting in response to operating forces. The speedup is then used by an ODE code component to compute the subsequent system condition (location, speed) after a chronon (simulation step).

(ii) inverse dynamics – allows to set system forces, knowing the system’s condition (location, speed) in individual moments of time. An example of such algorithms is a *Recursive Newton-Euler Algorithm* (RNEA).

The most important challenges for the physical library implementation are set by the solution of simple dynamics issue that might contain motion limitations of the two following categories:

(i) limitations associated with the assurances that the bodies cannot mutually penetrate,

(ii) limitations arising from various body connection restricting their freedom of movement.

The detailed aim of this study is to present test results associated with one of the rigid body simulation system algorithms. There are several groups of methods solving the dynamics issue of such bodies. They can be divided in the following way:

A. Methods based on the system’s inertia matrix. They use rigid body general motion system equations, as the one below:

$$H(q)\ddot{q}+C(q,\dot{q})=\tau \qquad (1)$$

where:
$q, \dot{q}, \ddot{q}$ – mean, respectively, generalized positions, speed and speedup vectors

H – a generalized inertia matrix depending on the q generalized position vector,

C – vector of generalized Coriolis, centrifugal, gravitational and other outside forces, having an impact on the system dependent on the generalized position and speed vectors.

τ – vector of generalized forces.

Application of this method is based on respective determination of C (by means of RNEA), H and $\ddot{q}$ and in the worst case possesses computational complexity of $O(n^3)$. An example of such algorithm is the *Composite-Rigid-Body Algorithm* [1].

B. Methods based on information propagation in kinematic chain. Limitation propagation from one body to the other goes in a way, that in particular moment of time the speedup computing of only one body is required. The computational complexity is expressed here as $O(n)$. The most common algorithm of this class is the *Articulated Body Algorithm,* elaborated in this study and described for the first time by Featherstone [2], then generalized and developed in [1].

C. Methods based on the Langrangian formalism. They cope with collection of independent equations expressing motions of all bodies and equations of limitations and forming these two groups into one great matrix equation. An example of such approach is the algorithm described by Baraff [4], applying the equations of the Lagrangian dynamics. It is a very useful method especially for closed-loop systems, while at the same time not competitive to methods from the first two presented groups or tree structure systems. The algorithm's efficiency is strongly dependent on the system matrix fill rate (matrix are usually rare).

The *Articulated Body Algorithm* (ABA) is the algorithm recognizing as one of the methods of the so-called coordinate reduced number or methods employing the so-called generalized coordinates, what means that the amount of parameters describing the system condition equals its freedom step number (apart from the methods, in which the condition variables number is greater than the system freedom step number, being one of the Lagrangian coefficient methods).

The basic ABA form is based on the Assumption that the given system is constructed in such a way that to the motionless base (Fig. 2.) the subsequent bodies – connectors - are connected, so that all of them , except the last one (called a peak or an effector) possesses one input joint linking it with the connector nearer to the base and one output joint, linking it with the connector farer from the base. The algorithm in its original form also assumes that all joints have only one freedom step – rotation around the "z" axis of a given articulated joint. The ABA employment forces particular connectors and joints numbering method, indexes of which appear in the following formulas:

- the connectors are numbered from the beginning of the base, increasingly to the effector's direction,
- the i joint is an input joint (located nearer the base) of the i connector.

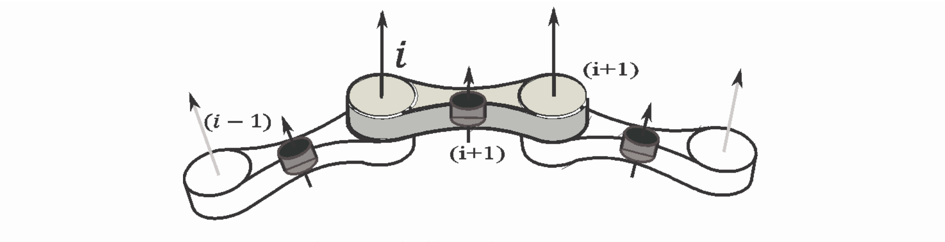

Fig. 2. A series kinematic system

All physical values describing the *i* connector are expressed in the coordinate system associated with this connector, due to which the conversions between the systems during computing of the algorithm's particular steps are required.

The Featherstone method can be generalized for tree structures, where the base is the tree's root, while every connector possesses exactly one input joint and unlimited number of output joints, forming the branches. The limitation of the motionless base can also be eliminated by a slight algorithm modification, e.g. it might possess full motion freedom in space. In general, the algorithm does not put any restrictions on the joints' freedom steps, what means that they do not have to be limited to one axis motion type only. Furthermore, there are numerous methods of algorithm optimization, paying special attention to parallel processing (by means of a "divide and rule" principle, presented in [3]), based on the fragmental tree division. The fragments are then treated as individual systems, every one of which might be analyzed in an independent way. Separate fragments are simulated by one thread and the results of the partial computing are applied in the main tree. The connectors are the previously divided subtrees, in this very moment treated as individual elements. The disadvantage of the ABA method is the fact that it does not apply to the closed-loop system simulations, which require a different computing approach.

A crucial part in the ABA algorithm plays the observation, that an individual connector speedup is always a linear function of its forces. If the whole system's motion would be interrupted by *f* testing force affecting any of the system's bodies, this body's speedup may be expressed as the following linear function :

$$\mathbf{a} = \mathbf{\Phi f} + \mathbf{b} \tag{2}$$

where:

a – body speedup,

b – theoretical speedup of the body, when f would equal zero,

Φ – matrix processing forces into speedups, such as $\mathbf{\Phi} : \mathbf{F^6} \mapsto \mathbf{M}^6$.

If motion of any body is unhampered, then Φ is a nonsingular matrix and the whole equation can be expressed in the inversed form:

$$\mathbf{f} = \mathbf{I}^A \mathbf{a} + \mathbf{p}^A \tag{3}$$

where $\mathbf{I}^A = \Phi^{-1}$ and $\mathbf{p}^A = \mathbf{I^{-1} b}$. In the ABA terminology, the whole system is called an articulated body, the body subjected to the testing force – a grip, I^A – articulated-body inertia of a given grip, and p^A is proper force aberration – the force to be pressed to a body, so that its speedup equals zero.

The thesis expressed by the equation (3) leads directly to the ABA algorithm. It may be proved that the equation (3) is correct for every connector through finding of I^A and p^A expressions. It occurs that these values can be set in the iteration way, starting from the *i* peak and going in the base direction. The full ABA algorithm consists of three loops, two input (from the base to the peak) – courses 1 and 3 – and one input one (from the peak to the base), acting as course 2. All formulas are expressed in the spatial algebra notation, connecting the translation and circular motion values into one six-component vector, defining anew the algebra operations in this structure.

Course no 1 (from the base to the peak) – speed propagation, initiation of speedups being a cross product of speed and initiation of force aberrations.

Tab. 2. Course I

Step	Operation	Condition	Signs
1	$v_{Ji} = h_i \dot{q}_i$		h_i - i-joint freedom step matrix $\dot{q}_i$ - i-joint scalar speed
2	$c_{Ji} = \dot{h}_i \dot{q}_i$		
3	$v_i = {}_iX_{\lambda(i)} v_{\lambda(i)} + v_{Ji}$	$v_0 = 0$	$\lambda(i)$ - index of the connector, for which the i-joint is the output one (parental i-joint index ${}_iX_{\lambda(i)}$ - matrix transforming speed vectors from the connector's system $\lambda(i)$ - for the i-connector system
4	$c_i = c_{Ji} + v_i \times v_{Ji}$		X - a cross product for speed vectors
5	$p_i = v_i \times^* I_i v_i - f_i^x$		f_i^x - outside force affecting the i-connector I_i - the isolated connector's inertia $\times^*$- a cross product for speed vectors

Course no 2 – (from the peak to the base) – articulated-body inertia and force aberration computing (I^A and p^A, respectively) for every connector.

Course no 3 – (from the base to the peak) – joint speedups computing and connector speedups propagation.

Tab. 3. Course II

Step	Operation	Condition	Signs
1	$I_i^A = I_i^A + \sum_{j\in\mu(i)} {}_iX_j^* I_j^a {}_jX_i$		${}_iX_j^*$ – matrix transforming force vectors from j-connector system into the system associated with the i-connector $\mu(i)$ – a set of all j-connector indexes, so that: $\lambda(j) = i$
2	$p_i^A = p_i^A + \sum_{j\in\mu(i)} {}_iX_j^* p_j^a$		
3	$U_i = I_i^A h_i$		
4	$D_i = h_i^T U_i$		
5	$u_i = \tau_i - h_i^T p_i^A$		τ_i – i-joint-based scalar value moment
6	$I_i^a = I_i^A - U_i D_i^{-1} U_i^T$		
7	$p_i^a = p_i^A + I_i^a c_i + U_i D_i^{-1} u_i$		

Tab. 4. Course III

Step	Operation	Conditions
1	$a_i' = {}_iX_{\lambda(i)} a_{\lambda(i)} + c_i$	$a_0 = 0$
2	$\ddot{q}_i = D_i^{-1}(u_i - U_i^T a_i')$	
3	$a_i = a_i' + h_i \ddot{q}_i$	

3. The algorithm's implementation

Real-time system simulation conditions cause that the employed programming engineering must take into account two basic priorities. The first one is the components' configurability, the second – time connections aspect, expressed in form of flow of activities and carefully selected architecture, making concurrent designing easier. There is a series of positive practices coping with means of implementation of configurable physical engine. One of the most interesting proposals has been described in the [5] project. In that case, the employed component approach is based on the assumption, that a library user uses it like a peculiar "block" series, every one of which is a functional entity, a "flight recorder", having some "tips", that can be connected with other components, creating complex systems in that way.

While creating the implementation presented in this document, particular emphasis was put on the following elements: object-oriented approach, simplicity of use.

Object-oriented approach destined for software creation is a standard nowadays and in the given context means that a library programming interface is a collection of abstract classes in C++ and is not a common list of C language functions, operating on data structures (for example WinAPI). The term "object-oriented" has here a different, deeper meaning and is associated with the fact that the library interface defines particular object classes, which can be created by the user by means of modeling complex dynamic structures. Apart from the component model, the user do not have to be worried about proper connection of "tips" of the formed models. In case of the presented approach, all connections within the complex model are created automatically on the basis of the description of the given object, what decreases the number of operations necessary for system configuration to be made by the user.

Simplicity of use. One of the basic assumptions was the creation of the easiest engine possible, as far its operation is concerned, what means that the final user should be able to make desired operations, such as system configuration accompanied by the smallest amount of labor needed (e.g. amount of code necessary for realization of a given task) and without possessing detailed knowledge of dynamics simulation methods. The following features are helpful in achieving this aim:

- forming objects by means of one function doing all necessary activities on the basis of delivered parameters (data is transmitted in form of a structure called descriptor; it possesses full set of parameters essential for the creating object),
- concealment of some complex system dynamic modeling aspects before the final user, which require possessing deeper knowledge and understanding connected issues, for instance kinematic loops operation, which are automatically detected on the basis of the existing connection network and internally operated in a proper way by the library, without any earlier user intervention,
- autonomic resource management. The users does not create the object directly by means of constructor's call, but through an appropriate library function taking care of memory allocation and return the final indicator to the object; all resources are automatically released during the physical module deterioration, the user do not have to remember about their removal,
- concealment of implementation details before the user (he/she has access to public library interfaces), what allows to pay attention to the most important functions, from the point of view of the final user, and protect before incompetent use of properties and methods of individual objects, through which an unstable simulation would have been caused; such an approach also ensures the implementation details to be kept a secret – they are the *know-how* of their author against users unauthorized to have access to full source code.

The programming interfaces has been designed, so that the class and function nomenclature identify in a unequivocal way the origins of the employed library. The created physical engine's working title is *Thor* and its global functions offering worldwide are accessible as static method of the class of the same name. All public interfaces use the *Th* prefix in their titles. The accepted standard of creating new classes and functions is Pascal notation.

Basic classes of the*Thor* library objects

Within the scope of complex dynamic system modeling, Thor possesses two basic object classes, by means of which the user may form complex compound structures:

- the rigid body (*ThRigidBody)* – elementary physical unit possessing specific shape and mass parameters,
- the joint *(ThJoint)* – a connection between two rigid bodies li miting their mutual movement.

Currently, the library implements three of the most common joint types:

- revolving (*ThRevoluteJoint)*,
- prismatic (*ThPrismaticJoint)*,
- spherical *(ThSphericalJoint)*.

There is also a possibility of creating objects representing outside interactions:

- the actuator – allows to set the force or moment of such force interacting with a single rigid body,

- the spring – enables forming force interaction between two rigid bodies, simulating a spring of previously user-set characteristics, like resilience and attenuation (the class is unavailable for the final user).

Another important class for the user is the multibody (currently in the testing stage; will be available in the future), which is a representation of a complex dynamic system made of rigid bodies and connecting joints.

Moreover, the library possesses own set of classes designer for mathematical operations in 3D (*ThVector3, ThMatrix33, ThQuaternion*) and specialized classes for *spatial algebra* operation.

Thor library operation

A model application using the library should per form several vital activities, such as: *Thor* module initiation (***Thor::Init*** method), physical objects' creation (of desired parameters – *Setup* method), system simulation in the program's main loop (***Thor::Step*** function in every iteration) and physics module de-initiation (***Thor::DeInit*** method). The *Thor::Init* method performs all preparatory activities necessary for work with the physics module, its call must occur before the use of any other *Thor* function, the *Thor::Step* function is responsible for simulation development in a set step of time, while the *Thor::DeInit* releases all resources blocked by the physics module and informs other code parts of the objects' deterioration.

The key role in the quoted example plays the *Setup* function, implementation of which is the main task of the final user. This method is responsible for creating and configuring the simulated dynamic system. A visual code fragment presents the necessary activities to form two rigid bodies and connect them to a revolving joint. The most important lines have been bolded.

```
void Setup(void)
{
   ThRigidBodyDesc bodyDesc1;
   ThRigidBodyDesc bodyDesc2;
   ThBoxShape boxShape1;
   ThBoxShape boxShape2;
   ThRigidBody *pRigidBody1;
   ThRigidBody *pRigidBody2;
   ThRevoluteJointDescjointDesc;
   ...
   pRigidBody1 = Thor::CreateRigidBody(bodyDesc1, boxShape1);
   pRigidBody2 = Thor::CreateRigidBody(bodyDesc2, boxShape2);

   jointDesc.mpLink0 = pRigidBody1;
   jointDesc.mpLink1 = pRigidBody2;
   ...
   Thor::CreateRevoluteJoint(jointDesc);
}
```

The overloaded *Thor:CreateRigidBody()* method forms a rigid body on the basis of its physical parameters' description (*ThRigidBodyDesc)* and description of the bounding box's shape (*ThBoxShape*). In this example it is a typical "box" – a cuboid – but there are so many function variants that they equal the shape library. The basic boundary boxes types are a box (*ThBoxShape)*, a cylinder *(ThCylinderShape)*, a sphere *(ThSphereShape)* and triangle-made arbitrary mesh (*ThMeshShape*) that should meet the protuberance condition. Dots standing before this method suggest that the user should in that place set the physical values (such as mass parameters, location, orientation in space, translation and circular movement attenuation) according to one's discretion. The *Thor:: CreateRevoluteJoint()* function creates a revolving joint, for which the essential matter is two-body provision, between which the following connection appears (*mpLink0 and mpLink1*). Dots standing before the function's use signalize that the user should deliver the other parameters (such as location and orientation in space, axis of revolution, location and orientation regarding the joint of connected objects) required for the currently forming joint.

4. Compound robot RT simulation

The operational correctness of the given ABA algorithm implementation was tested in a ROCH-1 robot model [6], a kinematic system structure of which is presented on figure 3.

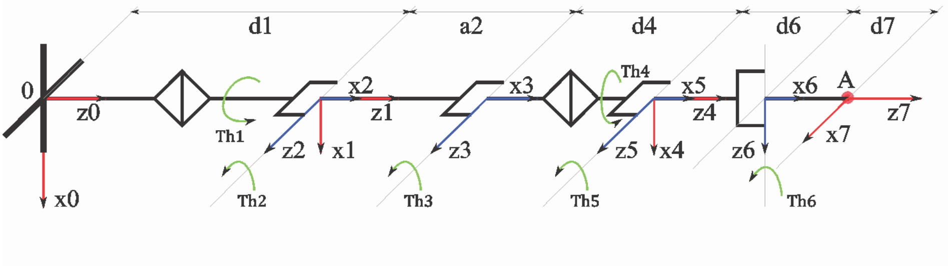

Fig.. 3. ROCH-1 surgical robot's kinematic structure

In the experiments performed, the robot was originally oriented vertically, forming a kind of folded physical pendulum possessing an symmetry axis of direction in accordance with gravitational vector.

Some of the robot's joint were then leaned from the original position, maintaining the „rigidness" of other connections. Such system configuration was a point of departure to simulation performance.

The aim of the tests was to check the algorithm's implementation regarding the basic mechanical rules, especially:

- relationships between the joints position and speed (whether this speed is a position derivative or not),
- compliance with the law of conservation of energy (whether the sum of all system elements' energies, accompanied by lack of outside forces, is stable),
- compliance with the second law of motion (whether the joints' speedups are proportional to the operating force moments).

Tests' conditions have been gathered in Table 5.

Tab. 5. Tests characterization

Test	Description	Conditions	Simulation parameters		
			Step [s]	Number precision	Integration method
1	Individual motion from any initial position	a) Initial inclination of joint no. 6, of 30 degrees	10^{-3}	single (float)	Runge-Kutta
		b) Initial inclination of joint no. 5, of 30 degrees	10^{-3}	single (float)	Runge-Kutta
		c) Initial inclination of joint no. 3, of 30 degrees	10^{-3}	single (float)	Runge-Kutta
		d) Initial inclination of joint no. 2, of 30 degrees	10^{-3}	single (float)	Runge-Kutta

2	Resultant motion	Initial inclination of joint no. 2, of 30 degrees, no internal friction	10^{-6}	double (double)	Runge-Kutta
3	Motion reality	Initial inclination of all joint equaling zero, in joint no. 6 a moment of force of set course	10^{-3}	single (float)	Runge-Kutta

On the following drawings of the resultant motion's stages and the chosen timings for the articulated joints.

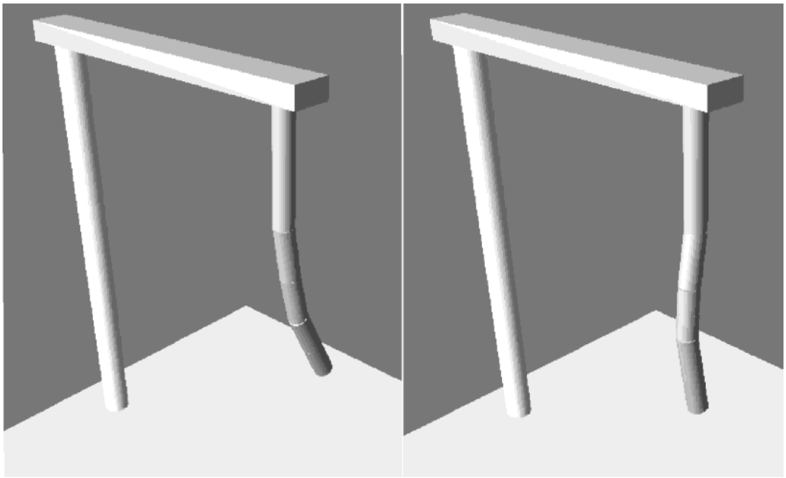

Fig. 4. Robot motion stages – simplified graphic chart

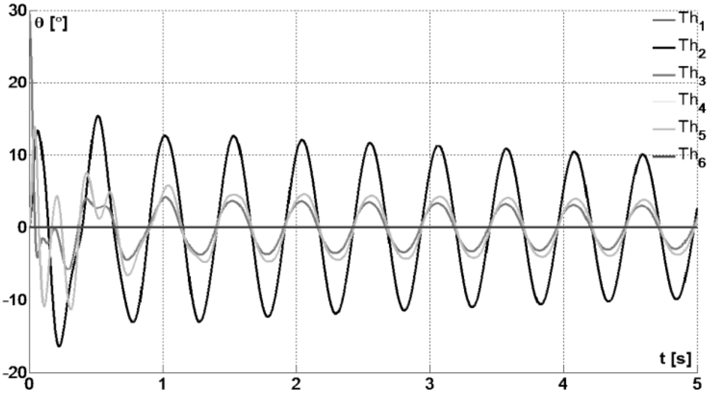

Fig. 5. Joint angles' timings for resultant motion

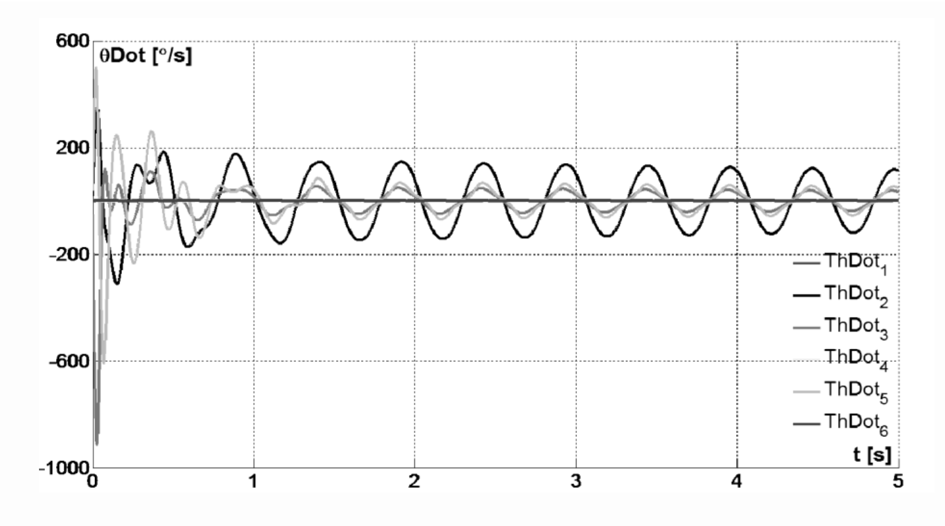

Fig. 6. Angular velocities' timings for resultant motion

Timings have an expected amplitude and shape. In the initial time, the motion is slightly chaotic and it gradually transforms into simple harmonic motion of decreasing amplitude caused by friction-based energy loss.

Eliminating friction, the system maintains the level of energy and its relative deviation from the averaged value do not exceed ± 2,0*e* –15, what characterizes the worked out software remarkably well. Energy deviation course is presented on Figure 7.

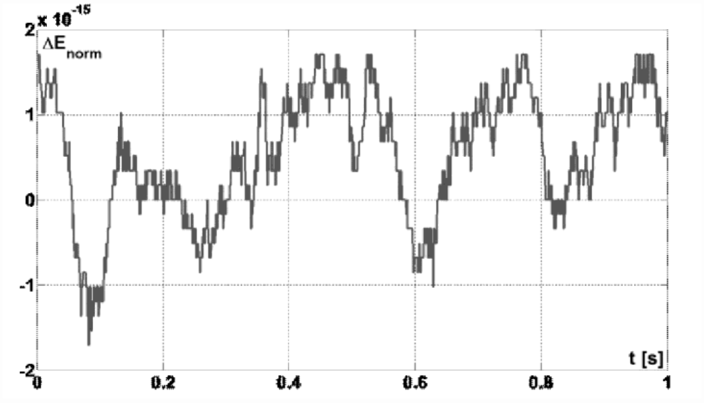

Fig. 7. Courses of system energy deviations from the averaged value

All computings were conducted on a PC computer, equipped with *Intel(R) Core(TM)2 Duo* (P8700) 2.53 GHz, 6 GB RAM processor, with *Windows® 7 64-bit* operation system. Demonstration run-times of the essential code fragments for tests 1 and 3 have been gathered and presented in Table 6.

Tab. 6. The tests' run-times

Code fragment	Description	Measure ment number	The shortest run-time [ms]	The longest run-time [ms]	The average run-time [ms]
ThorImpl:: Step()	One simulation step computing	512	0.03769	0.16577	0.04122

For comparison sake, demonstration code profiling results for the same tests have been provided by means of the Euler integration (Table 7).

Tab. 7. Tests run-times for Euler integration method

Code fragment	Description	Measure ment number	The shortest run-time [ms]	The longest run-time [ms]	The average run-time [ms]
ThorImpl:: Step()	One simulation step computing	512	0.01094	0.04175	0.01255

On the basis of the given results it can be seen, that the longest loop run-time is shorter than 0,2 [ms], so the simulation may be realized in the RT mode.

Conclusion

Alternative software for computer simulations of complex dynamic systems have been presented in this paper. Nowadays, the simulation is the first stage of new product manufacturing and it possesses a significant cognitive importance. Due to the simulators, the people are able to have access to the most complex phenomena, unavailable to the human senses in a direct way. They also enable detection of potential "weak points" of the designing product that may lead to a failure.

The software has a modular structure. A component being its main element, e.g. the so-called "physical engine", has been presented in this study. It is a competitive solution as far as the other programs are concerned, both commercial and freeware ones.

The ABA algorithm employed in this module, of computational complexity O(N), allows to perform elaborate real-time simulations. This has been proved by the tests realized for the ROCH-1 compound surgical robot, which is a good example of a complicated mechtronical device. It means that the software may have broader employment range, reaching even beyond medical robotics.

Summary

This study presents a project of an innovative software designed for complex dynamic systems' simulations and for real-time work. The module is characterized by high computing accuracy and is dedicated to mechatronical systems of complicated structures, consisting of movable parts connected by means of joints. The ABA algorithm employed in this module, of computational complexity O(N), allows to perform elaborate real-time simulations.

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Innovative concept of application and selected elements of control and powering unmanned aircrafts

Maksymilian Sobczak* Dominik Kozik**

Summary

Authors of this paper describe an innovative concept of employing unmanned aircraft as “a swarm of specialized unmanned flying objects used in case of emergency“. There were presented some constituents of the steering system of the flying objects with fuzzy controllers as well as an idea about how to propel such aircraft.

Keywords: unmanned aerial vehicles, UAV, unmanned aerial system, fuzzy regulator, propulsions systems.

1. Introduction

This study presents an innovative concept of unmanned aerial vehicles employment, based on their outside support in emergency situations through one or more specialized, unmanned flying objects. The concept is aimed at airliners flights’ safety coefficients increase.

The idea of solving emergency states of the airliners conditions the employment of various types and solutions associated with airline drives located on emergency facilities. This paper presents a concept of aircraft engines designed for specialized unmanned aerial vehicles.

2. Original concept of unmanned aerial vehicles innovative employment

The unmanned flying objects are the mechatronical objects. Their application depends on the equipment that they may take on board. Their employment is constantly

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broadening its range and is accompanied by device, system and measurement tools development. Nowadays, they are used in:

- border guard – in patrolling the countries' borders,
- fire service – for initial identification of fire areas, patrolling natural disaster areas and reaching inaccessible places with help,
- army – for patrolling battle areas, locating and destroying military objects,
- researches (for instance in checking animal species populations).

Modern aircrafts are one of the safest means of transport. Their high safety coefficient results from very detailed analyses of aircraft emergency situations. Additional factor influencing on the flights' safety improvement is implementation of the analyses' results in the currently constructing structures and development of procedures for emergency situations.

'Highly specialized swarm of unmanned flying objects used in case of emergency situations' is a concept of aircraft flight safety coefficients improvement by means of an outside support during such emergency situation. The term 'swarm of unmanned flying objects' should be understood as a group of unmanned aircrafts that are to complete together every task necessary for an aircraft's emergency state neutralization (Fig. 1).

Fig. 1. Specialized swarm of unmanned flying objects used in case of emergency situations

The term 'specialized swarm of unmanned flying objects used in case of emergency situations' describes an unmanned flying object taking off from an airport, flies to an aircraft in a particular emergency situation and is aimed at the neutralization of such situation. Its specialized state should be understood as an ability (adaptation) to complete a particular task, neutralizing a given aircraft's emergency state.

Example: an aircraft has a failure. It is impossible to operate by means of the elevator. In such a situation a specialized unmanned flying object is the unmanned aerial vehicle, that should be designed, so that it would reach the aircraft, stick to its flight control surface and play the elevator's role (Fig. 2).

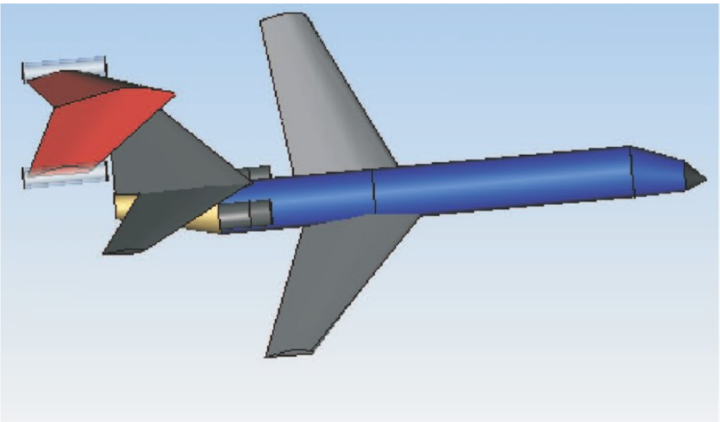

Fig. 2. Specialized unmanned flying object functioning as an elevator

The innovative character of this idea is based on raising the aircrafts' emergency situation solution probability by means of generalization of possible failures and using outside assistance. The emergency situation generalization deals with to its division into three groups and assignment of proper outside help. This division can be as follows: control systems failures, drive units failures, landing systems failures. The outside help should be understood as a specialized unmanned flying object supporting the damaged aircraft's flight.

Specialized unmanned flying objects may take the following aircraft's functions over:

- elevator, rudder, ailerons,
- drives (aircraft engines),
- undercarriages,
- navigational-pilot devices and systems,
- devices supplying the following energy types: electric, pneumatic, hydraulic.

Apart from the above-mentioned concept of the specialized swarm of unmanned flying objects, there are other unmanned aerial vehicles' employments, such as:

- intercepting/taking over of particular aircrafts,
- supervising of air traffic (so-called 'aerial traffic police'),
- deafening of air signals (electronic battles),
- aircraft reconfiguration during flights – the unmanned aerial vehicles may for instance constitute a construction grouping the aircrafts into dense groupings (V-formations) in order to improve long-distance flights economy.

3. General information of unmanned aircraft control

Unmanned aircraft control is steering of a multiparameter mechatronical object. It requires working out of numerous automatic flight-line control systems in dynamic (moving) frames of reference of high motion accuracy in space.

An unmanned flying object has particular dynamics. The essence of steering of such an aircraft is input and output values setting and creating such relationships between them, so that the flying object being steered should carry out orders arising from a task to be realized. Their control algorithms should be characterized by:

- efficiency and accuracy in the situations of: uncertain input data (measurement data) of control system, partial interaction to output values (control values),
- conservatism, when they are of no help, but the given situation is not hopeless,
- flexibility and creativity – in a potentially hopeless situation they should carry out all activities that may lead an aircraft out of an emergency situation; such activities should consist of systematically deduced tasks during performing of commissioned works,
- limitations in generating new procedures – maintaining of usefulness and stability in performing tasks.

An unmanned aircraft control consists of:

- maintaining particular flight parameters (height, speed, angles: of attack, inclination, tilting angle, thrust and engine speed),
- maintaining position in space (longitude, latitude, course, position regarding an aircraft, position regarding an airfield),
- completing a given task.

4. General issues associated with unmanned aerial vehicles' grouping control

Controlling a swarm of unmanned aerial vehicles consists of:

- steering an unmanned flying object one by one,
- maintaining a given, mutual position of the aircrafts,
- communication and connections within the swarm,
- processing data obtained during performing of the task,
- transmission of the obtained data among „specimen" in a swarm,
- taking action in case of emergency situation within a swarm and others.

In completing swarm tasks, a proper information flow among its object is a must. Communication with an aircraft being in an emergency condition and with local airfields is also helpful.

Communication systems should be characterized by:

- high action speed,

- work reliability,
- immunity to interferences,
- high channel capacity.

5. Model employment of fuzzy logic in steering unmanned aerial vehicles

A schema of initial project of autopilot module fuzzy regulator designed for inclination and tilting angles stabilization of an unmanned aerial vehicle [10] (Fig. 3) is presented below. It consists of two subsystems: for tilting stabilization and for inclination stabilization. The main system has five inputs: ‘ax’ and ‘ay’ speedups, elevator ‘dh’ inclination, ‘dL’ ailerons inclination and (common for the subsystems) ‘U’ flight speed. Two outputs of this systems are: elevator inclination signal ‘dh_wy’ and ailerons inclination signal ‘dL_wy’.

Steering algorithms require definition of: input and output membership functions and table of rules. Two stabilization subsystems - of tilting and of inclination – have analogous input and output values. A tilting stabilization module is presented below.

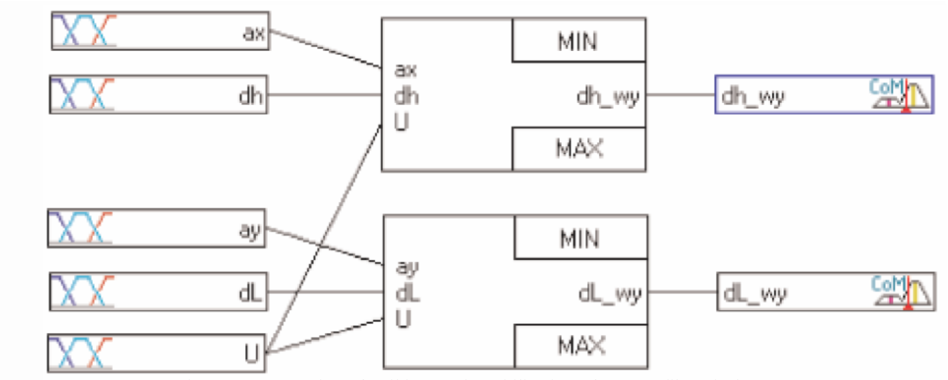

Fig. 3. Fuzzy regulator for tilting angle stabilization of PZL Koliber airplane.

Three membership functions routes (‘minus’, ‘zero’, ‘plus’) of an input variable ‘ax’ (analogous for ‘ay’) are shown on Figure 4. These functions, by means of tables of rules (elaborated later), determine the interaction range of input signals to obtaining output signal.

Four membership function routes (‘minus’, ‘zero’, ‘z’, ‘plus’) of an input variable ‘ax’ (analogous for ‘dL’) are shown of Figure 5. An additional variable ‘zero’ is a variable initiating automatic tilting angle stabilization in time when the control system interaction equals zero. Its route defines what are the borders of the automatic stabilization – it is also conditioned by the tables of rules.

A membership function route (‘small’, ‘great’) of flight speed input variable ‘U’ is shown on Figure 6. Two membership functions are sufficient for defining a linear independence between the variable value and its interaction to control.

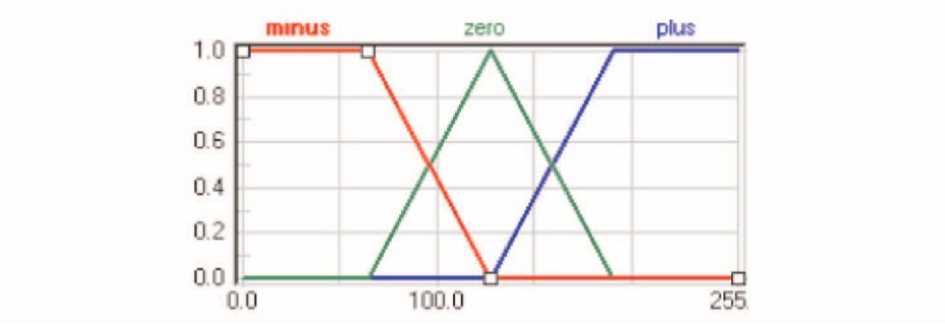

Fig. 4. Membership function route of variable ‘ax’

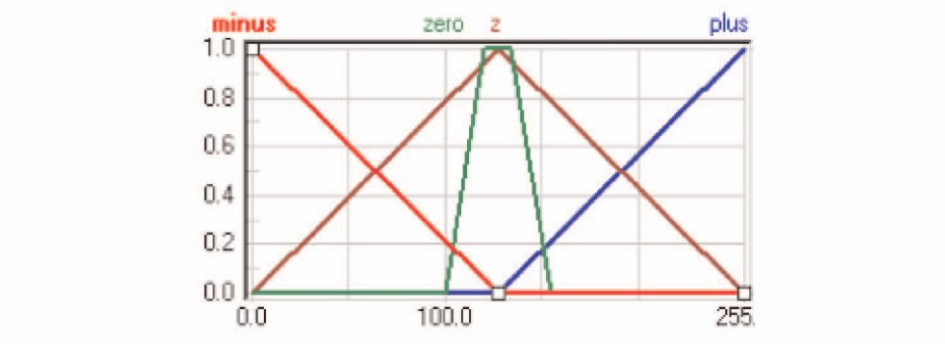

Fig. 5. Input variable ‘dh’ route

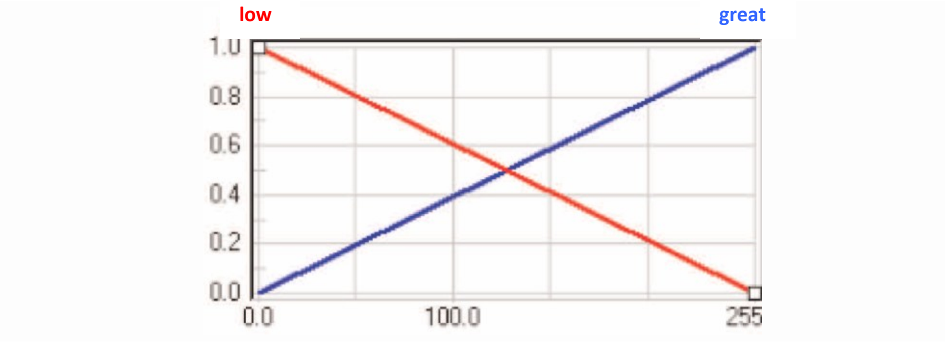

Fig. 6. Input variable ‘U’ route

The input variable ‘dh_wy’ (analogous – ‘dL_wy’), presented on Figure 7, consists of five membership functions (‘Dminu’, ‘minus’, ‘zero’, ‘plus’, ‘Dplus’). They are positioned in a linear way. The value ‘D’ determines extreme negative and positive values. These functions are used for control interaction increase during low flight speed and during direct controlling, without any active stabilization.

Relationships between input and output values are show in the following table of rulet (Tab. 1).

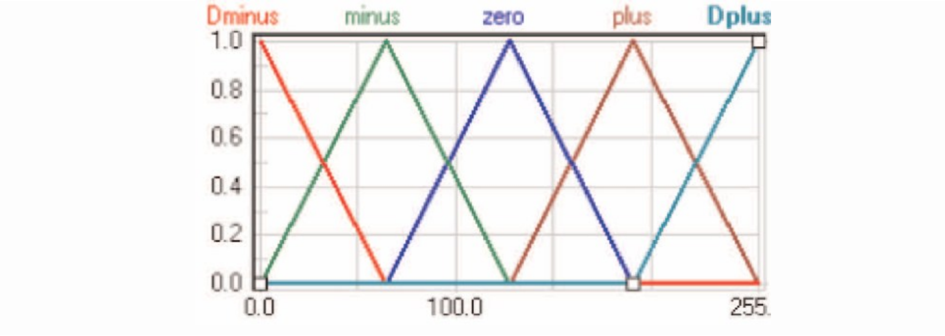

Fig. 7. Output variable 'dh_wy' route

The first two and the last rule of the table define direct interaction of control system to an unmanned aerial vehicle. The control system orders the tilting which is proportional to the elevator's inclination. If the control system do not change the tilting ('dh' is 'zero'), and angular velocity of both tilting and speedup 'ax' point to, for instance, unwanted 'zero' tilting', then the signal generated to the elevator is opposite (prevents from inexpedient inclination) – stabilizes the tilting angle.

The table presented below determines the interaction in the tilting channel. A table of rules for the inclination channel is analogous. Differences are associated with disparate determination of variables.

Tab. 1. Table of rules of tilting angle stabilization subsystem

#	IF		THEN		
	ax	**dh**	**U**	**DoS**	**dh_wy**
1		minus		0.10	Dminus
2		plus		0.10	Dplus
3	minus	zero	small	1.00	Dplus
4	zero	zero	small	1.00	zero
5	plus	zero	small	1.00	Dminus
6	minus	zero	great	1.00	zero
7	zero	zero	great	1.00	zero
8	plus	zero	great	1.00	minus
9		z		0.10	zero

Relationships between input and output variables are defined by a so-called surface airfoil (Fig. 8).

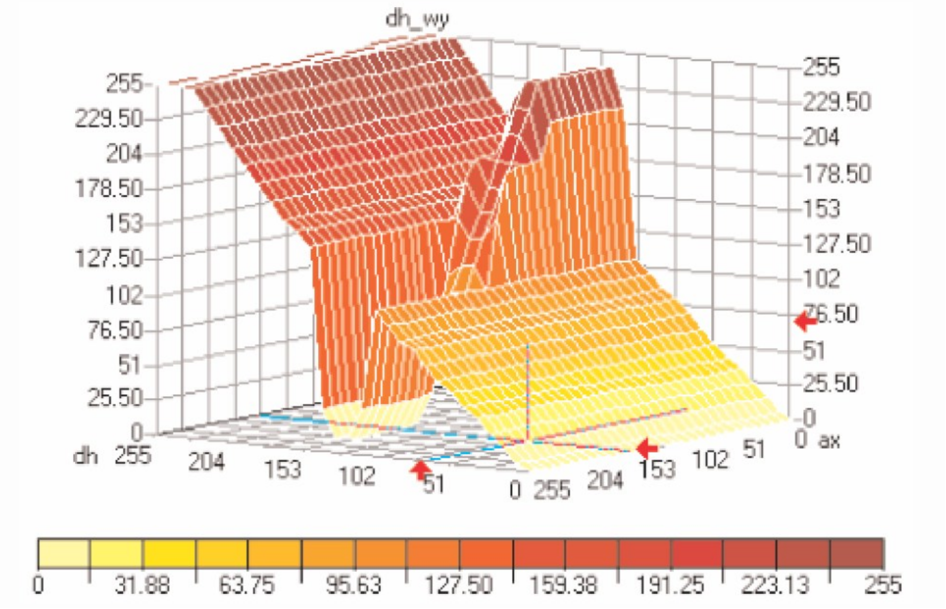

Fig. 8. Surface airfoil of the tilting stabilization subsystem

On the surface airfoil presented above, one can see two differing parts: a surface (bent over the horizontal level at an angle of 45º) and corrugation (positive and negative). The surface determines a direct interaction of control system to an airplane's tilting, whereas corrugations show tilting stabilization with zero set tilting values 'dh'.

The given fuzzy regulator is an initial version of stabilization modules employed in autopilots. It requires additional tuning to real parameters of particular unmanned aerial vehicles' types. The tuning is based on non-dimensional (8-bit, 0-255) input and output values calibration ('ax', 'dh', 'dh_wy') and on membership function and table of rules modification, aimed at control optimization.

The subject of fuzzy logic stabilization is realized by the Aviators' Student Society of Rzeszow University of Technology. Avionics of an unmanned airplane 'Prz-5 Wiewiór+' contains stabilization systems working similarly to the one presented in this paper [14].

6. Unmanned airplanes drive concept

Unmanned airplane drive, as an object of specialized emergency swarm, is an element of vital importance and high requirements. Depending on class of an airplane's failure, a particular unmanned aerial vehicle with particular engine type can be singled out. In case of an airplane's control system failure, a specialized unmanned airplane's engine should be responsible mainly for a swarm object's movement. In case of an airplane's engine trouble, a specialized unmanned airplane's engine is its basic component that is to replace the airplane's engine.

The idea of employment various types of drives of specialized unmanned aerial vehicle swarm ranges from performed tasks' optimization, their application generalization, to solving various failure types.

The engine of a specialized unmanned aerial vehicle, designed for flight control surfaces control, should be characterized by:

- thrust of values equaling lift forces of a given flight control surface of an airplane – in case when an unmanned aerial vehicle is not to incline structurally like the flight control surface of an airplane, but it is to interact on this airplane in a similar way as this surface, yet by means of the engine's thrust,
- a possible thrust inversion:
  - thrust inversion should occur with the use of change of the airscrew angle of attack into a negative one (in case of propeller engines),
  - thrust inversion should occur with the use of control nozzle and lid system (in case of flow engines),
- the smallest possible dimensions and weight in case of an unmanned aerial vehicle, which functions as rudder in an aerodynamic way, e.g. is a constructional movable part aimed at interaction with an airplane in a similar way as flight control movable surfaces.

The engine of a specialized unmanned aerial vehicle, designed for thrust , should be characterized by:

- rocket-type structure – engine is the main component,
- small flight control surfaces that, having been docked to an airplane, might be transported to another unmanned flying object,
- huge thrust – similar to the airplane's thrust that is Begin repaired.

Conclusion

Aviation is becoming increasingly common and requires theoretical studies outlay, as well as tests verifying particular theses increase. We offer an up-to-now unknown way of safety coefficients improvement by means of emergency situations support, based on the unmanned aerial vehicles. As the title suggests, currently it is only a concept. It requires practical verification of: realization possibilities, work load, financial outlay and realization time. Moreover, we offer the tests' directing or intensifying aimed at air transport reliability improvement by means of development of unmanned aerial vehicles and existing airplanes/cargo aircrafts cooperation.

In achieving these aims we can be supported by objects' control, based on the fuzzy logic laws. It is an alternative to classic approach of control systems production. Modern engineering techniques allows to create so-called artificial intelligencies and objects operating on its basis. We hope that many-valued logic will influence the improvement of control systems efficiency coefficients.

Summary

An innovative concept of unmanned aerial vehicles' employment has been presented (a 'specialized swarm of unmanned flying objects used in case of emergency situations'). Chosen elements of controlling the unmanned flying objects with the use of a fuzzy

regulator, as well as a drive concept of these aerial vehicles have been depicted.

Keywords: unmanned aerial vehicles, UAV, unmanned Flying objects, steering, fuzzy logic, aircraft engine.

Footnotes

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III

Intelligent house

SSID – Intelligent House Control System – selected equipment solutions

Ryszard Leniowski*, Wojciech Kogut*, Krzysztof Kwartnik*

Summary

The paper presents an original concept of the control system hardware layer of "smart home", based on available technology (mechanical, electromechanical and electronic), widely known and respected standard for data transmission and original solutions in the field of algorithms and software (implementations). This is one of the examples of mechatronical solutions, which are characterized by low implementation cost and simplicity and are open to future modifications,

Keywords: intelligent house, building automation, embedded controllers applications.

1. Introduction

Mechatronical devices are an increasingly common means of equipment solutions, tightly connected with the meaning of the term „intelligent house”. Nowadays, two of those meanings are essential. According to the first one, “intelligent houses” are highly automated objects of high functionality and increased level of safety. The second one is associated with homes constructed according to a specific philosophy aimed at dwelling comfort and household members safety maximization, accompanied by exploitative costs minimization.

According to the authors, an „intelligent house” may be built in phases, without meeting a specific philosophy’s assumptions even in the designing stage. Functionality planning in the designing stage makes its future realization easier. However, it does not exclude the “intelligence” improvement in the existing buildings. The presented solution of the system hardware layer is associated with the first notion of “intelligent house”, taking into its range even larger group of objects.

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In such an approach the hardware solutions of an „intelligent house" can be divided into four groups: sensorics, executive elements, installations-mains and management system. The main task of this system is gathering information from sensors, their processing and controlling them by means of the executive elements and the "intelligence" built in the algorithms, as well as on the basis of these pieces of information. It is worth observing, that such system is a connection of many modern elements and technological solutions belonging to the classical domains, such as: mechanics, electronics, automatics and computer science, so it can be described as a mechatronical system.

This study presents an original concept of "intelligent house" control system hardware layer., based on the available technologies (mechanical, electromechanical, electronic), widely known and highly valued data transmission standard and the original solutions within the scope of algorithmics (implementations). This solution is characterized by very low construction cost, simplicity and openness to future modifications, being in accordance with the users' needs. It also complies with a mechatronical rule that assumes striving for strong system integration, algorithmics and software, so that the programming solution will be developed functionally and possess a modular or component structure.

The original, Polish solutions (for instance in [1] and [2]) are still limited to prototype systems construction and testing. These systems, due to lack of national financial support, are usually not developed anymore.

2. Building automation system standards

It is considered that the development possibilities of traditional electrical wirings have been practically used up. The amount and complexity level of devices installed in modern buildings force to seeking alternative solutions as far as powering, controlling and diagnostic methods are concerned. Installation devices producers create their own control and regulation systems, implementing new automatics elements into building techniques. The most well-known and spread are EIB, X10 and LonWorks.

KNX (earlier - **EIB -** *European Installation*) is a standard existing from 2002 that have connected three previously worked out EIB, EHS, BCS standards. In 2004 it was regarded as a European standard, and from 2006 is a worldwide standard. It is a completely new, open electro-installation system, worked out by the European leading producers. KNX is managed by *Konnex Associacion* [7]. It is used for enclosing, controlling, signaling, regulating and monitoring electrical devices, installing in building industry. It replaces the classic electrical wiring (Fig. 1).The EIB topology is based on tree structure. Its basic part is a *line*, into which up to 64 devices can be connected (with additional clutches – maximum 256 devices in total). For bigger installations the lines are linked into zones (up to 15 lines), and the zones – into areas (up to 15). Such a configuration enables installing even 57,600 elements in one installation.

The system's main advantages are:

- big energy savings associated with exploitation of a building,
- resistance to failures,

- only one, common control cable (the system is clear, economical wiring, lesser fire risk, easy and cheap service),
- easy requirement realization, issued by the users,
- high flexibility (future system extension or its reconfiguration do not require any wiring change).

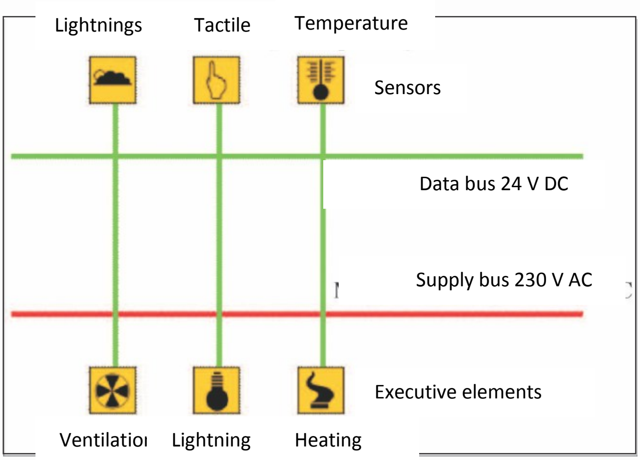

Fig. 1. KNX/EIB installation schema

X10 – a system worked out in Europe (Scotland), but it gained its first popularity in the USA. Its elements communicate with each other by means of a digital, modular signal transmitted by the existing electrical wiring (230 V/50 Hz) and radio access network (future implementations). Each executive module possesses two identification registers. One of them allows to choose a house code in A-P range. The second one allows to choose a unit code in 1-16 range. As a result of these configurations, 256 possible devices or groups of devices are to be controlled. The identification code enables the modules to be grouped into functional sets.

LonMark – is a system based on LonWorks platform, supported by the following companies: Hewlett Packard, IBM, Motorola, Microsoft, Philips, Toshiba. The system was constructed in order to manage production processes. The LonWorks technology allows to connect various devices after any communication medium. One of the characteristics of the network built on the basis of this technology is "intelligence dispersion", e.g. lack of a central driver. It is considered to be complex [8]. It employs the devices that can contain different drivers, but from the point of view of communication interface they have to be visible as the so-called "Neuron Chips". Depending on the software, it is a 2-6-layer hardware-software structure, employing the LonTalk communication protocol.

RadioBus – signal transmission between RadioBus system elements undergoes by means of radio communication, so control cables are unnecessary. The system's advantage is that it can be quickly and easily installed and dismantled, and in the case of move – taken with. It is a curious solution designed for small public utility buildings, such as shops, restaurants, offices or doctor's offices. The solutions implemented into this system have also been added to the EIB and to KNX.

PowerNet – PowerNet is a variant of the EIB system. It is designed for objects, in which the electrical wiring is already installed. From the wiring point of view, the system is similar to the X10 one. Its main feature is signal transmission on two different frequencies. Comparison of received signals with the given standard and elaborated error correction procedure enable proper reception in case of any interferences and information loss. PowerNet currently conforms to the KNX specification.

3. IHMS system architecture

Assumptions. The IHMS system is based on several assumptions resulting from observation of home installations and devices functioning, human habits, their needs and desires, financial restrictions and mechatronical concept of an intelligent home.

1. Every device (of any level of complexity) has a built-in microcontroller, responsible for its functionality and communication with the other system elements;
2. Simple structure and reliable operation. The majority of people use only the main functions of devices. The remaining options, after first attempts, are hardly or never switched on again.
3. The system has a control unit – a PC computer. PC computers are a natural bridge connecting the building control system with the Internet, enabling remote monitoring of an object. Energy saving PC computers' cases, taking less than 50 W of power, are able to work continuously and no to increase electric energy fares.
4. The system installation consists of a three-phase powering network and control network, using a four-twisted pair or radio connection in the 2,4 GHz band, guaranteeing the range of 400 m.

Installation – IHMS system installation consists of two buses: energy and control (Fig. 2a). The energy bus is realized as three-phase, five-wire network, divided into several sections. It always runs within the walls, in the coving area of 20 cm width. Lines directed to one- and three-phase receivers are led out of it.

A small house has no more than 2 sections, big – 3-4 or more, depending on its function. Such division causes easier failure diagnostics and its elimination, employing the efficient sections. Each section possesses residual-current, miniature circuit and lightning breakers. The lightning protection is two-stage – the first for the whole object, the second – for the chosen, most sensitive and valuable receivers.

The control bus consists of a signal bus and two control cables (24 V). IHMS system hierarchical architecture is based on the tree structure. The basic part of it is a line containing up to 255 drivers (practically – to 31). The line connects local drivers forming a group, in which one plays a supervisory role, and the others – a minor one. The master driver is called a group driver. If the system consists of one group driver, at the same time it plays a role of a master computer, and the installation is called a small one. An example of such structure is presented on Figure 2.

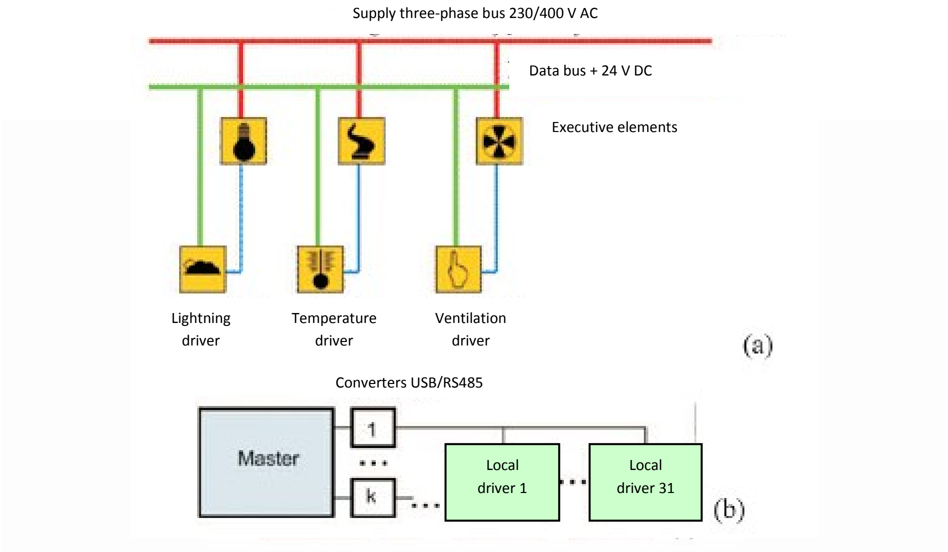

Fig. 2. (a) IHMS system installation schema; (b) system with one group driver

The line is realized in the RS485 standard, works in the half-duplex mode and uses a popular UTP5 wiring with four pairs of twisted-pair cables (including one active). The remaining cables constitute a reserve destined for a quick transmission realized in the full-duplex mode (for high-frequency processes drivers). The USB/RS485 converters directly connect the lines with PC computer's ports. A low energy consuming PC computer is preferable in this case (for instance with Intel Atom processor). Working constantly, it can play a role of a home server and a master driver for the control system.

In case of bigger installations, the lines are added to the group drivers that can support up to 4 lines. The group drivers connect with a master unit by means of Ethernet (Fig. 3).

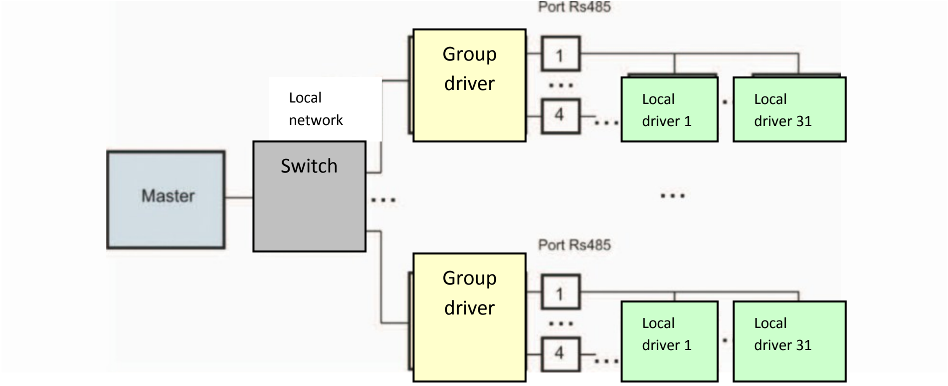

Fig. 3. IHMS system medium and big installation schema

Group drivers employ 32-bit RAM processors, while local drivers are constructed on the basis of cheap (or very cheap) microcontrollers ATmega8 [3]. The local driver may possess its own bus (for instance I^2C), used for connecting remote sensors or executive devices (Fig. 4).

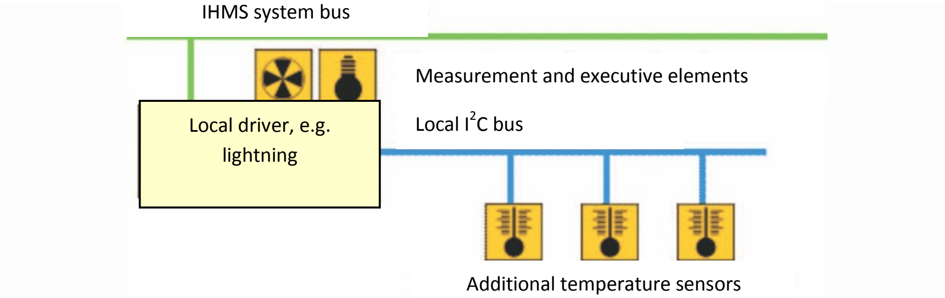

Fig . 4. Local driver with I^2C bus

This solution is very natural for such systems, as a multi-point water temperature measurement of central heating container. To one I^2C bus several temperature sensors are connected, what allows to determine heating dynamics (energy loading) or cooling dynamics of the container.

4. IHMS - chosen hardware components

The majority of tasks associated with modern building's functioning might be realized by means of simple and cheap controllers. The more complicated ones (for instance thermal energy control – producing and distribution) may be assigned to the drivers built on the basis of DSP systems (for example TMS320F24xx, TMS320F28xx) or ARM Cortex3 [4]. The most difficult tasks (image processing, graphic models synthesis) associated with safety may be realized by dedicated SoC systems (for instance Texas Instruments – OMAP, TI- Da Vinci).

The basic local driver employed in the IHMS system is a set of modules (up to three), so-called „sandwiches":

- Measurement module,
- Universal executive model,
- Driver module.

Measurement module – consists of a set of sensors to analogue values measurement: temperature (two channels), humidity and lightning intensity. Possesses 4 binary inputs linked with a PIR sensor and optical barriers (or reed switches). CO, CO_2 and CH_4 sensors and smoke detectors are connected optionally (for previously chosen rooms). A view of a measurement module is presented on Figure 5.

The measurement module may be fastened to the majority of typical installation cases (after breaking off of the corners, it fits into a surface mounted gang box or flush mounting box). Since the local driver deals mainly with room service, the measurement module is equipped with a wireless communication interface. Cooperating with a typical household appliance remote control (such systems have numerous reserve registers, into which some dedicated functions can be set), the local driver is controlled by the user just like any other household appliance. The only condition is that the pilot works according to the RC5 standard.

Fig. 5. Measurement module with I^2C bus

The measurement module has I^2C bus set, due to which additional analogue, binary or meter inputs can be connected to the local driver. This option is used for instance to control the usable warm water (UWW) system, consisting of gas-fired or solar water-heater. In this system temperature of the seven essential points is measured.

Universal executive model – consists of two power channels designed for electrical energy receivers control, supplied by a single-phase network. Possesses the "walk through zero" detection of line-to-neutral voltage. Power of a single channel reaches 600 W. Optiisolators are used to its control and they ensure galvanic isolation. Control signal is a PWM signal of 8-bit resolution. The executive module do not have to be integrated with the other driver elements and it is usually positioned in a separate box, located nearer the energy receiver. Figure 6 presents this module, installed in a flush mounting box, employed to bulb-power control.

Fig. 6. Universal executive model

Apart from the bulbs, the executive module controls the rotational speed of pumps installed in the central heating and usable warm water systems.

Driver module – is connected with the measurement module by means of two gold-pins and by means of a cable with the executive module. Contains a feeder, RS485 interface, joints and buzzer (Fig. 7). If the situation requires, two such modules are located in common boxes (Fig. 8).

Fig. 7. Driver module

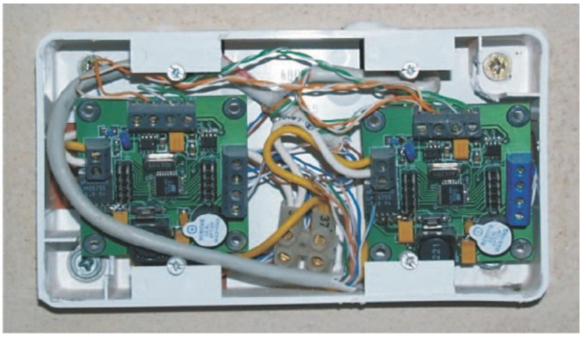

Fig. 8. Double driver system

The basic local connector may play many roles, for instance:

Room condition controller (including internal safety).
Lightning driver.
Outside safety controller,
Garden or orchard guard station (for example weather monitoring, paying special attention to apple scab growth).
Weather stations.
High-power electric furnace driver.

A typical electric furnace is a system of three resistors (resistant heaters) that may work in a triangle or star system. It is a very simple method of regulating its power, often supported by a two-condition regulator linked with a temperature detector. More accurate control of a three-phase electric stove requires replacing of a universal executive model with a dedicated work module and with a dedicated power module. The proposed solution is based on the fact of switching three resistors (resistant heaters) into three transistor keys IGBT type, working on the straight three-phase voltage by means of 6D bridge. Such a system allows to control power more accurately, at the same time employing the PWM modulation, and react on emergency conditions detected by the built-in, necessary protection, so exceeding the maximum temperature and pressure differences (indirect water-flow measurement). The constructed power module is presented on Figure 9. The module processes the power up to 24 kW. Three white systems (TLP250 – Toshiba plays a galvanic isolation role and IGBT transistors power driver.

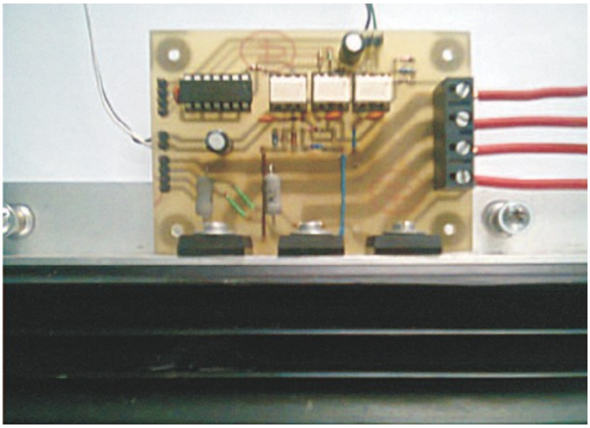

Fig. 9. High-power transistor driver module

The IMHS system consists of another executive modules, dedicated to valve heater control, accompanied by a valve lift (the valve is equipped with a simple location encoder). Description of this module, as well as its operation, and due to the subject's extensiveness (a kind of dedicated position servomechanism) is a subject of another publication.

5. IHMS – hardware layer transmission protocol

Building automation system standards, elaborated earlier, use data protocols of various complexity level. KNX/TP1 package possesses changing length and consists of 8 to 23 bytes of data. Contains the following areas: controlling, the source's address, destination address, data length, data, total. A typical LonTalk protocol package, also called ANSI/EIA/CEA-709.1, consists of 12 bytes composed into a few so-called layers: headline, information address (format, knot, group, domain. One of the first protocols was the EnOcean of 14-byte length, including 2 synchronizing bytes, identifier, 4 data bytes, four identification bytes, status and control sum. In case of the building systems, the other essential protocols are ZigBee PPDU, Modbus RTU and DALIi of the simplest possible structure – 2-byte output frame and 1-byte input frame.

The IHMS local drivers contain a dedicated software responsible for a particular function (for instance an indoor regulator or a weather station). The communicate with the master system by means of a simple protocol (little amount of code), called a MIKROBUS. It possesses the following features: stable, 8-bit frame, Master – Slave operation mode, built-in false reading protection, any transmission speed (for the line). The frame contains a byte of address, a byte of function, data fields and checksum.

```
struct frameMIKROBUS
{
unsigned char address;
unsigned char fun;
unsigned char data0;
unsigned char data1;
unsigned char data2;
unsigned char data3;
unsigned char data4;
unsigned char CRC;
}
```

The first byte contains a device's address, to which the information is directed. If its value is 0, the frame is received by all devices (broadcasting). An address byte consists of an address line (three older bites) and five bites describing the device in a given line. The information are transmitted from the Master driver to the Slave driver and in the opposite direction are controlled by means of a set of functions. As a rule, they do not require any confirmation, but several key functions do require the Slave driver's confirmation. Control byte has the following structure:

10	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
Function flag		Function number					0/1
							0-record 1-reading

A function flag is a set of four support parameters, making the internal function realization on the Slave driver easier. The subsequent five bites determine the function number, giving 32 possible combinations. The last bit controls the data flow, record and reading direction. Currently there are 17 defined functions for the room driver and a few functions for pump and valve drivers. For example, as for the room driver, function number 5 means "read the humidity" and allows to gather information about the current humidity of a given room and the set levels: lower and upper one. Its best developed functions are the lightning control ones, with an optional mood choice. They are available only to the room controlling drivers, in which at least a few ceiling, floor and wall lamps have been installed.

The system hardware layer evolution

The two-year IHMS system operation allowed to verify the original claims and gain valuable experiences that will be employed in the future system's versions. It occurred that, for instance, the older household members cannot break the routine barrier, as far as the modern installations are concerned. This issue was solved in a way, that traditional switches were added – they play a role of binary signals for the local drivers. The most curious and at the same time the most difficult problems that came out during the system's run-time were connected with emergency states of the country wiring installations. They coped with multi-hour electricity losses, appearing both in summertime, and in wintertime. As for the summer, the amount of energy produced by solar thermal collectors reached 10 kW and have to be continuously received and stored in containers. The pump operation stoppage in hydraulic circuits may lead to severe and expensive failures. Originally, the emergency supply system was planned for 3-hours of working time. It occurred, however, that the energy system breakdowns sometimes last even up to 5 hours, which twice led to extreme overload of solar supply hydraulic circuits. In order to avoid such situation in the subsequent seasons, new solutions were designed, both in the hardware and in the software layer, and are to be implemented soon. They deal with the IHMS system connection with the emergency supply system, microprocessor-controlled and consisting of: solar batteries, stabilizing battery and an independent inverter. Such a system is to ensure the independent supply of the solar system water heating circulating pumps..

The second issue, but of the same importance level, is associated with thermal energy management, produced by a hybrid system from four sources: solid fuel furnace (wood-fired), gas furnace, solar system and electric furnace, cooperating with the container and separatory funnel system. The solid fuel furnace, the most difficult to control, requires the local driver of bigger computing power employment, accompanied by a so-called engine interface for fan control. For this particular aim, the most suitable is the ARM7 processor family with Cortex3 core or TI controllers from TMS320F280x-60 series. Since the ARM7 processors are produced by numerous companies and free-software supported, this choice is right. They also possess one great advantage – a LAN network, built-in driver. They can operate as the local drivers (units with slower clock and smaller memory capacity) or the group drivers ("stronger" systems). The hardware standardization on this level should make their programming and various modifications easier. An additional chief asset of AT-mega8 to ARM-Cortex3 migration is the LPCXpresso module, designed by NXP company and manufactured in such a form that it can be divided into two parts (LPC-Link + Target) of the board [5] presented below (Fig. 10).

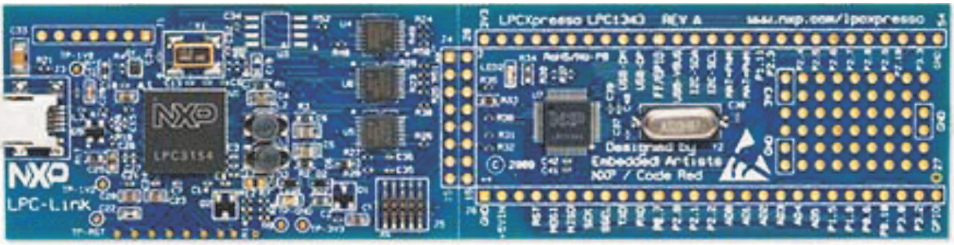

Fig. 10. LPCXpresso module [5]

The LPC-Link part is a hardware-software debugger with ARM9 processor, JTAG interface and a USB port to PC-oriented communication. On the other hand, the Target part is a prototypical board with ARM7-Cortex3 processor (for example LPC1769), manufactured in a universal format. The LPCXpresso is sold for 99 zlotys, so the price is very attractive, encouraging the user to employ it in the IHMS system.

The future works over the IHMS system predict a soon implementation of *plug and play* mechanism into the local drivers. It requires, however, the software layer expansion on the local drivers level and on the group drivers level. In the ATmega8 such a procedure was unavailable. The employment of ARM7-Cortex3 destroys this barrier. Autodiagnostics of the local drivers will be expanded, too.

Parametric room identification is planned as well. It is expected to be realized on the local driver level. It is a task associated with new heater power control algorithms by means of valves linked with miniature position servomechanisms. The prototype system consists of a valve, DC motor, planetary gear with big gear ratio, rotary optical encoder, clutch transforming the transmission shaft's circular motion into the plane motion of the needle of the valve and the local driver with built-in power amplifier DRV880 type. It is a miniature monolithic system, operating in the 4T bridge system, manufactured by Texas Instruments. With this particular power system the TMS320F28069 driver cooperates in the best possible way (the same producer for both parts). The system contains 2 engine interfaces, what allows to lower the unit cost of the miniature servomechanism. The tested installation comprises of 20 valves connected to 2 separatory funnels of 12 and 8 segments. This requires the employment of at least 10 drivers. Their number cannot be decreased. Theoretically, a concept of absolute encoders connected through a multiplexer to only one driver may be considered. This particular driver, by means of a multichannel separatory funnel might control the corresponding valves and DC motors power systems. Yet, this idea requires use of hardware that is not produced at present.

There are also other software layer development plans, for instance associated with an object's internal safety or implementation of electric energy parameters measurement on a building's junction because very often they do not meet the given standards, indirectly affect the increased amount of failures and breakdowns of sensitive hardware and decrease dwelling comfort.

Conclusion

The study presents an original concept of a hardware layer of an „intelligent home" as an example of mechatronical solution, competitive to expensive, commercial standards. Its main characteristics – low production cost, simplicity and openness to future modifications – should favor its spread, but on the condition that a promotion activities in the hardware producers, engineers, designers and users should be conducted. Slightly modest, initial system hardware base may be easily expanded. Manufacturing the original devices is not troublesome and appears to be accessible for students and graduates of electrotechnics, automatics and mechatronics faculties, even those, who have short experience in this field. The implementation of the *plug and play* mechanism into the IHMS system will make this assignment easier with absolute certainty.

This paper also mentioned the wireless buses, increasingly common devices in home automatics (for instance ZigBee system developed by ZigBee Alliance). Although the IHMS system is based on signal cable transmission, it assumes a possibility of cooperation with the ZigBee network. The group driver acts as a connecting bridge and plays a role of a ZigBee coordinator.

The authors are aware that the lack of strong financial background considerably stops the test on new IHMS system elements. Yet, the experienced that have been gained so far shows, that there are alternative directions of building automation system development, significantly cheaper than the ones currently existing on the market. High price of commercial systems (for example KNX/EIB) will be the main factor blocking their spread among individual Central and Eastern European investors who are not the beneficiaries of the European funds given to this particular goal [6].

In the Polish reality a simple and cheap system, just like the IHMS or similar to it, might create a valuable environment of businessmen and specialists, competing with foreign companies, treating our national market as a distribution area. The whole scientific background of these companies is located outside the Polish border, due to which the universities of technology students are treated as specialized engineers. Time is of the highest importance because similar systems are currently being manufactured in China.

Summary

The study presents an original concept of a hardware layer control system of an “intelligent home”, based on the available technologies (mechanical, electromechanical and electronic solutions), widely known and respected data transmission standard and the original resolutions within the scope of algorithmics and software (implementations). It is also an example of mechatronical solution, characterized by low production cost, simplicity and openness for future modifications.

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Selected problems with control in a one family house

Marek Śnieżek*

Summary

The paper presents some problems with single-family home control and shows examples of solutions. They were made and tested by the author in a family house in a few years. Some solutions may be used in larger buildings. In principle, each of these systems can operate autonomously. Then, each of which requires the individual sensors. More benefits can be achieved by combining them in an integrated system. Then the sensors are connected to one controller, and data are exchanged between "interested" controllers. This creates the distributed control system. This solution has the advantage that the system could be designed, and made in stages, and the development of control algorithms and systems integration along with the collection followed the author's experience, and expert knowledge acquisition. The author gave up control of a centralized computer, due to the high energy consumption of contemporary computers. Nowadays, the computer seems to be unnecessary because system management can be carried out, e.g. by a mobile phone with a dedicated application.

Keywords: intelligent home solution, controlling: heating, ventilation, security systems.

1. Introduction

The modern home consists not only of wall and roof, but also – in an increasing degree – a set of technical-mechatronical devices, ensuring the dwelling comfort. Such devices are equipped with detectors gathering data, electronic control system, usually accompanied by a processor, and executive elements. Structure of such a system requires combination of knowledge of the following fields: mechanics, electronics, computer engineering and automatics. It is a typical assignment for a mechatronical engineer.

The subject of ecology, ecological home and energy saving has recently become trendy. The energy saving need arises from the economical aspect. It is sometimes associated with investing necessary financial resources at the very beginning, so that they reimburse and

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begin making profits.

For example, producers and salesmen offer solar collectors, recuperators and thermal pumps. From the author's experience it can be concluded that in many cases these are the right solutions, especially for large and medium facilities of special employment. Some are lured by their advertisements and install such systems in single-family houses. The author also thinks that they are not the products designed for such small buildings. From the survey of available resolutions, for instance [4] and [5], it can be assumed that there are not enough cheap and simple products on the market, enabling to be used in practically every household, increasing its comfort of use.

Solar collectors example. The employment of solar collectors to produce usable warm water is becoming more and more popular. This solution is economically justified, for instance in a hospital, which all the year round uses a given amount of water. The use of such collectors in a school facility is controversial, however, because during the most sunny months the school is closed. In case of household employment of the collectors, their installation costs around dozen thousands zlotys[1].To this sum one must add service, additional room for large container and electric energy used, for circulation pump operation, costs (as well as protections in case of energy loss). What is more, during winter, it is obligatory to heat the above-mentioned container by means of traditional heating methods (only few are installing a second, smaller, container used only in wintertime, with additional automatic features). Furthermore, building's architectural change (appearance deterioration) and, sometimes, its non-optimal location regarding directions of the world should also be remembered. Actually, the usable warm water production cost for a 2+2 or 2+1 family (after several years, very often only 2) is not high. Having added a second, parallel trend (associated with water saving), it may appear that such an installation will never pay for itself.

Summing up the above example, everyone has to make an economic calculation, taking into consideration one's needs and possibilities, also the long-term ones.

The following part of the study deals with the author's solutions in several chosen aspects of controlling a single-family home.

2. Ventilation control

For room ventilation the following ventilation channels are the most common ones: exhaust channels and ventilators. In the older buildings, the latter were hardly installed (due to draughty windows), while nowadays some parts of the ventilation systems works on the basis of an inverted line (blowing the air instead of exhausting it).

It is also known that in the summer such natural ventilation seldom works, while during wintertime it can suck uncontrolled amounts of heated air in (especially in case of windy weather). Is there any simple and inexpensive solution to this problem? It seems yes. Airflow control is would be enough.

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[1] There are numerous EU and bank programs, allowing to lower this cost to a few thousands zlotys.

The system consists of:

- ventilation system:
  - mechanical filter,
  - airflow speedometer (Fig. 1),
  - fan of adjustable rotational speed ,
  - throttle (as an option, usually the filter's resistance is enough),
  - thermometer, hygrometer,
  - local driver.
- exhaust system:
  - airflow speedometer,
  - throttle (Fig. 2),
  - fan (in the bathroom or toilet - optionally),
  - gas quality detector (kitchen vapor, toxic gases, carbon dioxide, carbon oxide),
  - thermometer (option), hygrometer (bathroom),
  - local driver.
- local driver.

The ventilator and exhaust systems are installed in every channel. A central driver (one only) is integrated with the local drivers and monitoring system, although it can operate on its own.

The throttle's opening lid is controlled by a model-making servomechanism. The airflow speedometer is pinwheel[2].

The local drivers are responsible for input data gathering (airflow, temperature, humidity), transmitting them to the central driver and the executive elements control (throttle, fan) on the basis of the given control values. Communication between the drivers takes place with the employment of Modbus RTU protocol (RS-485 bus or by radio).

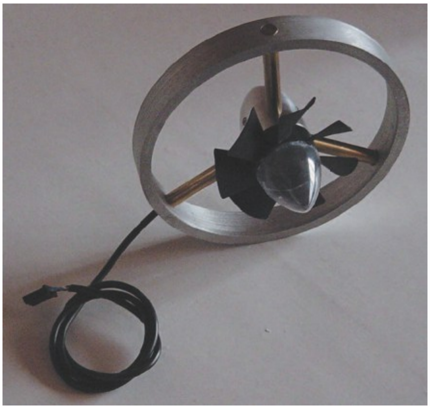

Fig. 1. Airflow speedometer

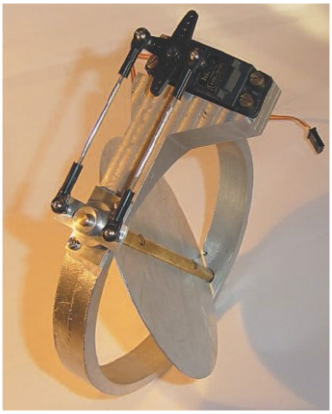

Fig. 2. Throttle

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[2] The ultrasonic flow meter is currently being tested.

The most complex element, regarding software, is the central driver. Formally speaking, the air mass balance should be left, what is almost impossible. The voluminal balance might have been a real one, although there are significant features interfering it, such as lighting fireplace or operating central heating/usable warm water furnace with open combustion chamber (change of the volume as a result of higher fume temperature). Chimney measurements cause additional problems and have been omitted by the author. Draughtinesses are another problem, thus the control has to be more intuitive. The following criteria were accepted:

- any ventilation system cannot operate with the inverted line,
- air quality must be ensured,
- air replacement minimization during winter (when home is heated),
- if possible, in the wintertime one should ventilate during the day, when the outside temperature is usually higher than at night,
- during the summertime one can ventilate more significantly; ventilation minimization during the day (when there is hot outside, so that the inside temperature would not increase) and maximization at night (cooling the interior). In this way a “cheap” air-conditioning can be obtained.
- transitional periods should fit the heating cost minimization in,
- working fans whirr minimization,
- taking into account the fireplace and operating central heating/usable warm water furnace operation (with open combustion chamber)
- window condition (open/closed)[3] and signaling the necessity of their opening.

As can be easily seen, the control is multi-criteria. Additionally, one would have to work in both weather forecasts (including the long-term ones) and household members’ presence. As far as the driver is concerned, it is possible and at the same changes values of individual parameters, but daily data inserting is onerous. The author have used the data from the household members’ authorization, long-term weather forecasting is helpful and not at all onerous. The system had been “tuned” for several seasons and applies the author’s needs.

The author is aware, that the system presented below is currently in the prototype stage and when it was to be commercially available, it would have to be subjected to numerous tests. A proper complement to the system would be a configuration packet, including significances for separate criteria, according to the user’s desire.

The installation requires a checkup. Despite the air filtration, the anemometers require constant cleaning (impeller vanes). Bearing mounting is also important because the flows are not large, thus the gradual migration to ultrasonic sensors. Fan engines are constructed with compact coils. Rotary speed adjustment is more difficult. Full tension control period with variable number of periods was chosen.

3. Window shades control

Electric motor shades were installed in the building’s window openings. Every shade has its individual driver enabling lowering/lifting a given shade to any level. There is also a central shade driver. The whole system was added to the overall commu-

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[2] The data come from the other driver (shade driver). Option in general.

nication network ModbusRTU, allowing to gather information associated with shade lifting and their opening/closing control. In the window sashes, the window opening sensors were installed (like in the alarm systems), so from the central shade driver level the information about opening of one of them is available[4].

The central shade driver's software seems to be relatively simple. The range of available functions also raises no doubts and repeats itself in all commercially available solutions. In the presented driver, an astronomical clock was built into (calculating the sunrise/sunset and dawn/twilight time – civil and navigational) [1] and the moment of lowering/lifting the shades was made conditional with daily changing sunset/sunrise times[5]. This fact released the user from frequent reprogramming the lowering/lifting shade times. In addition, a limited astronomical control, for instance "lift the shade 20 minutes before sunrise, but not earlier than at 5:30", make this system's functionality even better. The driver may also possess a lightning and temperature detector. The most important central shade driver functions are presented below:

- controlling by means of the driver's keyboard or radiopilot:
  - all shades,
  - single shade,
  - a group of shades (group defining).
- work mode:
  - leave,
  - vacation,
  - a week (Monday – Friday, Saturday, Sunday),
  - individual (for every day of the week),
  - astronomical (Monday – Friday, Saturday, Sunday),
  - astronomical with limitations (Monday – Friday, Saturday, Sunday),
  - lightning level consideration (sunny/cloudy),
  - public and stable holidays and movable feasts.
- lifting/lowering shade level (may be dependent on the temperature).

Such complex functionality of the driver, especially number of possible work modes, complicate its configuration. For configuration in the question-answer mode a LCD display and 4 key are used. Since the configuration process repeats for every shade, copying of settings between shades was made available. When the setting are identical or only few parameters undergo slight changes, it considerably hastens this process.

On the other hand, such comprehensive setting possibility causes that the configuration process is performed only once per several years[6]. Having in mind the possibility of remembering up to 3 completed configurations, their recall is very quick. There is no doubt that the central driver has a built-in real-time clock automatically accepting time change into the summer/standard and vice versa.

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[4] Window condition information may be used in ventilation control.

[5] In 2003, when the driver was invented, it was an exceptional solution.

[6] The author made any changes to the configuration in 2007 for the last time.

4. Alarm host and access control

The alarm host improves the inhabitants' safety and protects their property. The host collects and processes the information from the sensors of:

- windows and door opening (shade driver sensors),
- glass breaking,
- PIR motion,
- smoke, methane, carbon oxide (data may come from the ventilation driver),
- optical barriers,
- video cameras, including those with automatic intruder detection (future).

The remaining supplement is the household members' authorization during wicket and front door opening. All data are registered and later they can be used by other systems. The alarm host realize notifications about current occurrences, but the type of the notification depends on the situation's character. It is obvious that one must act differently, when the glass was broken during the household members' absence, and differently in case of carbon oxide detection during their sleep.

5. Electronic electricity meter

Such electricity meters are available in the commerce (and are inexpensive), but the author made the one himself, so as to have an impact on its functionality and compliance with the remaining system elements. The meter's functions are the following:

- voltage and phase current measurement (*true RMS*),
- voltage frequency measurement,
- real, reactive and apparent power measurement,
- real, reactive and apparent energy measurement – temporary (for instance one-hour),
- total energy and individual stages in a given period measurement,
- data registration on SD card (1..60 second programmed),
- overload signaling (short- and long-term),
- Modbus RTU communication.

The electricity meter is not only a valuable source of information for the user, but it can also be employed by other system elements, for instance by the central heating driver. On Figures 3 and 4 model current routes are presented.

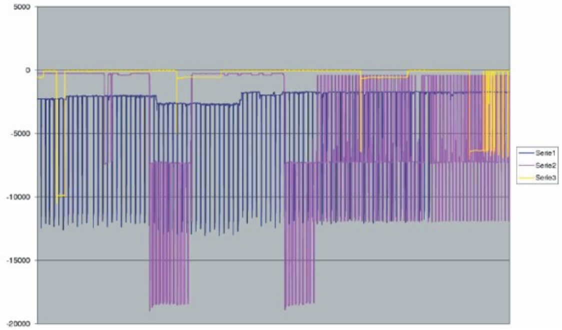

Fig. 3. Current routes with hot plate on (a few burners)

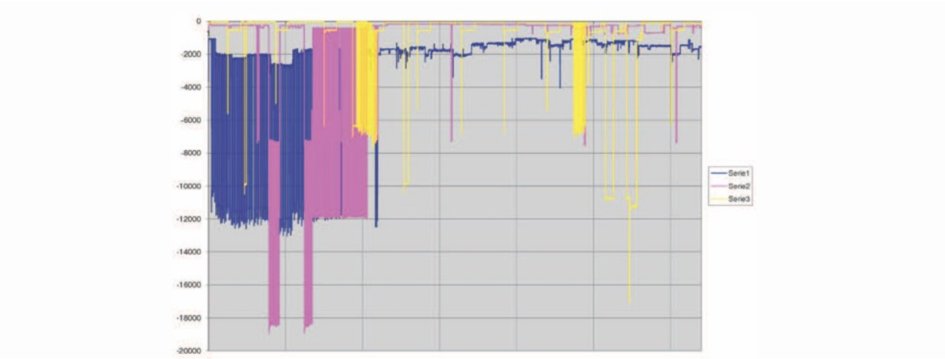

Fig. 4. Current routes – a few hours

6. Central heating (c.h.) and usable warm water (u.w.w.) control

C.h. control. Advertising materials of numerous companies associated with heating technique inform that 1°C increase of temperature in a room raises the heating cost of 6%. As a result, a question arises – is it worth to splurge valuable money? Where to fix thermal and financial comfort limit? Everyone has to answer these questions individually. The author, analyzing the problem, manufactured a driver giving broader possibilities than the standard drivers. A universal c.h. gas furnace (20 kW) with a u.w.w. container (120 l per 4 people), equipped with microprocessor channel plate. The producer do not make the communication protocol available to furnace communication, so the author was "forced" to its "diagnosis". It is vital that the furnace needs no changes at all[7]. A c.h. water temperature set value depends on the inside and outside temperature (the heating curve[8]). At the same time, other energy sources and needs are taken into account:

- preparing meals, lightning and other indirect thermal resources:
  - 10 kWh/day in form of electric energy, mainly for preparing meals,
  - electric energy consumption analysis and prediction,
  - „activities" forecast manual implementation.
- fireplace – a significant source of energy – approximately 10 kW,
  - manual, initial switch-on signaling.
- household members' presence plan,
  - day and night reduction,
  - longer departures.
- building construction and location regarding directions of the world,
  - whether and how firmly switch on, particularly in case of the upcoming sunny weather,
  - spring/summer transitional periods.
- ventilation – don't turn on heating before and during ventilation[9].

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[7] Safety issues are of the utmost importance in case of warranty loss during the initial period.

[8] The drivers taking the heating curve into account, though more expensive, are available in the majority of the producers.

[9] As for the author, having employed the ventilation control system, there is no need of air the home by means of window opening during the wintertime.

U.w.w. control. Is a container to be always filled with hot water? The answer may be "no" – warm water is enough, especially when there is a dishwasher in a house, and water during the day is used only for minor activities, such as hand-cleaning, preparing vegetables for a meal, etc.

U.w.w. preparing algorithm is associated with:

- cold and container water temperature measurement,
- water consumption and weekly history (averaged) measurement,
- water consumption prediction,
- furnace turn-on time set and water temperature value set,
- circulating pump control.

It should be added that the biggest u.w.w. savings are connected with family members' washing and require their self-discipline. When everyone washes approximately at the same hour, the savings can be even bigger. Unfortunately, when time differences are considerable, another turning on of the furnace may be necessary (increased gas consumption) due to warm and cold water mixture (having used a part of warm water) or washing in colder water (in summer it may be pleasant, but not necessarily in winter).

7. Weather station

Fig. 5. Weather station [2]

The weather station presented on Figure 5 has two functions:

- gathers information about current weather and registers it (history). The values measured are:
  - wind direction and power measurement,
  - air temperature,
  - relative humidity,
  - atmospheric pressure,
  - amount of liquid precipitation (snow – melting),
  - dew presence,
  - sun exposure,
  - soil moisture (a few zones and layers - option).
- transmits information to other drivers (RS-485, Modbus RTU).

All measured data are written together with their measurement time (a timestamp) on SD memory card.

8. Garden irrigation control

Garden irrigation is the next issue that can be solved by means of automatic control. Tap water is increasingly getting more expensive, but a beautiful garden gives pleasure not only to its owner. The employment of a given driver may lead not only to water consumption saving (irrigation at the best day time and by the smallest amount of water possible), but is also time-saving.

The system consists of: water distribution system and water sprinklers (professionally installed or hose-made), detectors and driver[10].

Priorities can be set variously, but the author uses in this study the criterion of water consumption minimization. An irrigation driver uses the data from the weather station (no additional detectors are needed in this case) and controls several irrigation zones (lawn, bushes, trees, beds, the northern side). Each zone has its own priorities regarding the frequency, abundance and irrigation initiation moment. As for control, the most complex one is the bed zone because the priorities change proportionally to the plants' growth. The driver has a function of irrigation stoppage in case of forecasted rain or garden duties, as well as a function of long-term weather forecast implementation, what enhances or weakens the significance of irrigation.

The employment of rainwater, gathered in an underground container, improves the economical balance of tap water consumption., but creates new control problems, for instance whether to use the water supply and irrigate a bit heavier than it is presented in the minimization criterion of water consumption, or which zone should be the most privileged. It should be added that the forecasts very often do not turn out to be real and then the worked out strategies are not optimal.

The Figure 6, presents temperature and humidity values, while the Figure 7 presents the values of atmospheric pressure in one of the months.

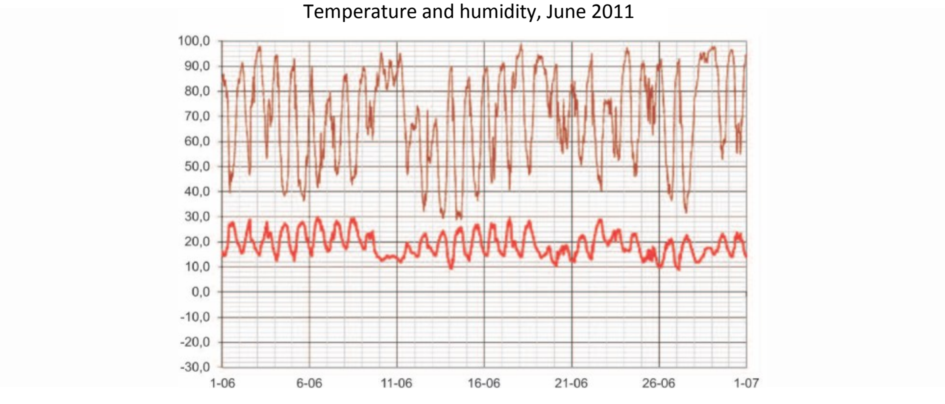
Temperature and humidity, June 2011

Fig. 8. Temperature and humidity diagram.

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[10] Drivers available in the commerce usually allow to periodic, cyclical solenoid control without any soil moisture measurement and do not apply to weather forecast (irrigation during the rain).

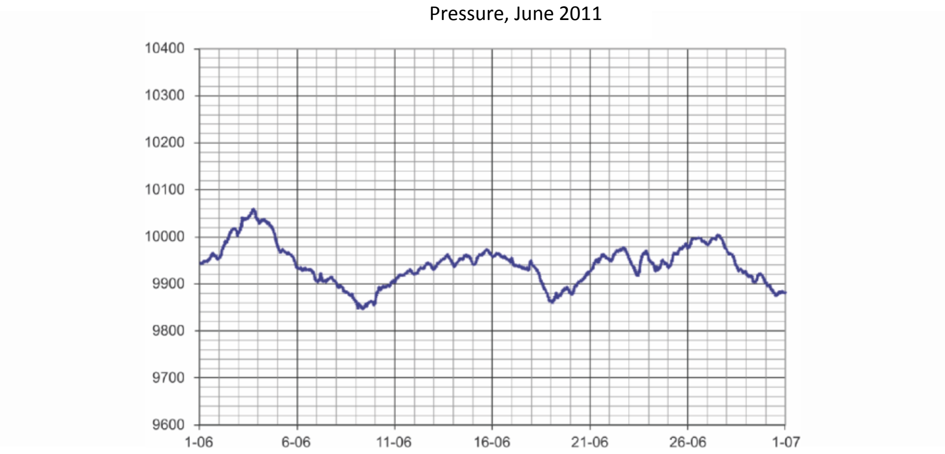

Fig. 7. Atmospheric pressure diagram

Summary

This paper presents chosen control problems in a single-home family and their solutions. They were made and tested by the author within several years. Some resolutions can be employed in even bigger objects. In general, every system can operate autonomously, but then every one of them claims that more benefits can be obtained by connecting them to form an integrated signal. Then the detectors are linked to one system, which organizes, while the data are exchanged are exchanged between any "interested" drivers. As a result, a fuzzy control system appears. It possesses the advantage that the system was to be created stage by stage, while the development of control algorithms and system integration occurred simultaneously with gathering the author's experience and gaining specialist knowledge. The author abandoned the computer-aided centralized control due to high energy consumption of contemporary computers. Currently the computer also seems to be unnecessary because the system can be managed for instance by means of a mobile phone.

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IV

Technological problems

Chapter 1

LTCC1 application for performing microfluid systems

Karol Malecha*

Summary

In this paper, general information[1] on Low Temperature Co-fired Ceramic materials and manufacturing processes is given. Alternative application of the LTCC technology in field of microfluidics is discussed. Development, technology and properties of the LTCC-based microsystem for urea determination in fluids and microfluidic system for detection of heavy metal ions in water are presented.

Keywords: Low temperature co-fired ceramics, microfluidics, microsystem, thick film.

1. Introduction

Analytic procedures used in modern biological, (bio)chemical and medical researches require from the experimenter the employment of a series of manual activities: taking and initial preparing of a sample, conducting a proper chemical reaction in appropriate conditions, dividing and marking of the products. All mentioned actions are time-consuming, thus the time of products' detection also becomes longer and the increase of consumption of (often extremely expensive) reagents and bigger amount of waste. In order to eliminate these inconveniences, a concept of microfluidic µTAS and LoC systems have been proposed (*Micro Total Analysis System, Lab-on-Chip*, respectively). Such systems allow to conduct various biological, (bio)chemical or medical real-time analyses, as well as fully automated, gas- or liquid-based samples of volume measured in micro- or nanolitres. This significant volume analyte reduction enables not only reagent consumption reduction, but at the same time considerably shortens marking-time of given substances. The importance of this issue is even more emphasized by organizing separate, annual international scientific conferences named: *Miniaturized Chemical and Biochemical Analysis System - µTAS and MEMS*, that were

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[1] Low Temperature Co-fired Ceramics

singled out on the beginning of the 90s. To the first microfludic system examples or attempts of their realization in Poland one can recognize the following: integrate miniature gas chromatograph [1], thermo cycler for DNA duplication [2], microsystem based on microdialysis for glucose, lactates, glutamates and potassium ions determination [3], microreactor for urea determination [4].

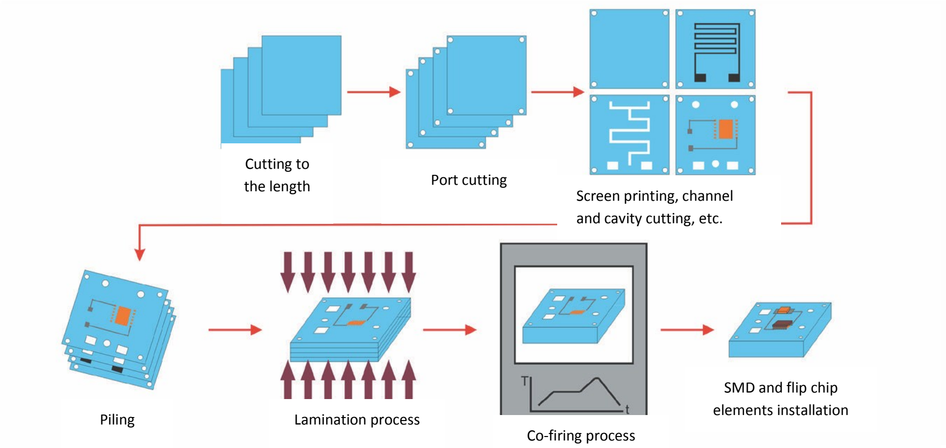
Strong development of microelectronic technologies at the end of the XX century have caused that for microfluidic systems' designing mainly silicon and glass were used initially. Silicon-glass μTAS and LoC systems were produced by means tools and processes characteristic for the semiconductor technology [5]. However, high material and technological apparatus costs, employed to 3D silicon microprocessing, caused that the researchers began to search for new, less expensive material that could have been used for microfluidic systems construction. Nowadays, polymeric materials technologies (these are, for instance, polycarbonates, polyimides and silicons) [6] and Printed Circuit Boards (PCB) [7] are being employed more frequent for this purpose. Modern Low Temperature Co-fired Ceramics (LTCC) and the associated technology is cheaper than the semiconductor technology and the materials used in this technology are more resistant than silicon and glass. What is more, new microsystem designing process is considerably quicker and easier. However, the LTCC ceramics' advantage over plastic materials is the possibility of its easy integration with numerous electronic and optoelectronic sub-assemblies, as well as the employment of well-known processes and materials characteristic to the thick-film technology. The advantage of the LTCC ceramics regarding the printed circuit board technology is the possibility of producing microfluidic systems of considerably higher density of electric and liquid connections. Moreover, copper – widely used in the printed circuit board technique – is not chemically inert and may significantly influence the proper microfluidic system's operation. The materials used for LTCC systems' production are more physically and chemically resistant than the materials applied to the printed circuit boards manufacturing.

This study presents model microfluidic systems worked out by the author on the Faculty of Microsystems Electronics and Photonics of the Wroclaw University of Technology. The described systems are as follows: microsystem of urea liquid-based determination by means of electrochemical method and microfluidic system for heavy metal ions water concentration measurement. It is worth noticing that the microsystem employing the potentiometric detection for urea determination have been drawn out in cooperation with the leading Polish Department of Hybrid and Analytic Microbiosystems in the Institute of Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences in Warsaw, where the works on practical employment of such detectors and microsystems are currently being conducted.

2. LTCC technology

The LTCC ceramics is a composite material. It may consist of crystallizing glass (for example (MgO-Al_2O_3-SiO_2, CaO-B_2O_3-SiO_2) or a mixture of glass (B_2O_3- SiO_2, Pb-B_2O_3-SiO_2) and ceramics (usually Al_2O_3) [8]. The LTCC ceramics' properties may be easily adjusted to the user's needs by means of employment a combination of materials of proper physical or chemical characteristics. A typical LTCC tape in the raw state (before the co-fire process) consists of powdered ceramics (45%), glass (40%) and organic matrix (15%). The organic matrix plays a role of a binder, binding ceramics and glass powders and ensuring proper mechanical properties of the LTCC tape before the co-fire process.

A technology using low-temperature co-fired ceramics was worked out in the late 80s of the XX century. It was also known under the term GreenTape™ and employed mainly for hybrid electronic systems and VLSI (*Very Large Scale Integration*) systems casings production [9]. A typical LTCC technological process is based on the multi-layer monolytic system production consisting of several up to several dozens of ceramic tapes. Each layer may be covered by a network of conductive pathways. The conductive pathways of individual layers are electrically connected with the use of ports filled with gold or silver conductive grease. A simplified technological process route of multi-layer LTCC module production is presented on Figure 1.



Rys. 1. Technological process route of LTCC structure production

In the first stage, the LTCC tape is cut to the dimensions of the presented system. Then alignment openings and ports are cut. They are usually made by means of a piercing die (70-200 μm diameters) or a laser (20-50 μm diameters). In the next step with the use of a screen printing method the ports are filled and the conductive pathway are marked on (common greases: PdAg, PtAg, Ag, Au, Cu) and thick-film reactors (for example resistors). The following stage is tape cutting by means of a laset or cutting die. Microfluidic structures are cut within the tapes (for instance channels, containter, etc.). Then particular ceramic layers are piled and connected with each other in the lamination and co-firing process. During the former a constant connection of unfired ceramic tapes is made. In general, the ceramic tapes are molded under 20 MPa pressure and increased temperature (70°C). The lamination process temperature should be higher than the LTCC tape organic binder softening. After the lamination process, the ceramic module is co-fired in the multi-zone or oven-type furnace in two-stage temperature profile, in air or nitrogen atmosphere (Cu-based greases). During the first stage (up to 450ºC) volatile compounds, forming the organic binders, vaporize. During the second co-fire stage (up to 875ºC) glass grains are heated to the temperature exceeding the softening point. Then the liquid glass moistens ceramic grains. When the temperature decreases, the glass hardens and creates a solid material (Fig. 2).

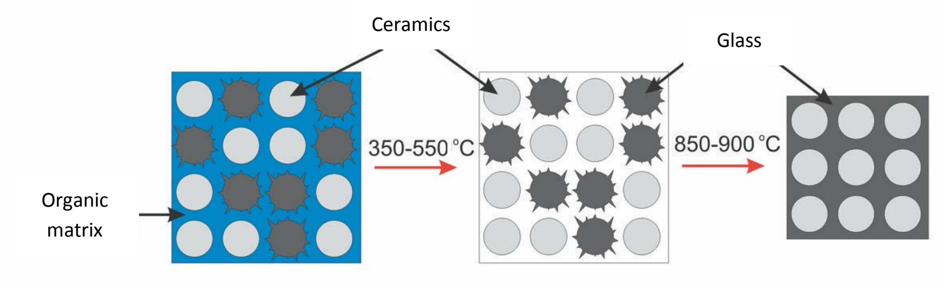


Fig. 2. A simplified model of co-firing raw LTCC tapes

During the last stage, on the bottom and outer surfaces of the co-fired module active and passive elements are installed by means of standard techniques used in microelectronics (for instance SMT, flip chip, wire bonding, etc.).

The LTCC systems are typical MCM (*Multi Chip Module*) structures. Such a device can be defined as a multi-layer module of significant number of internal electric connections between non-cased integrated circuits, mainly of great integration scale, covering up to 20% ground surface, combined into one large functional unit [8]. The MCM system is a solid mechanical construction.

Currently, the LTCC technology is used not only for electronic system multi-layer casings, but also is employed in microsystem technique for various micromechanical and microfluidic devices construction [10, 11].

3. LTCC-made microfluidic systems

Modern microfluidic systems are usually built from several integrated functional blocks: sample transportation (micropumps, microvalves), initial sample preparation (micromixers), microreactor, in which the right analytic reaction takes place, and detector [12, 13].

This paper presents model structures of two microfluidic systems made by means of the LTCC technology. The demonstrated microdevices may operate independently, but they may be connected as well, forming more complex microfluidic system.

The microsystem for urea liquid-based determination by means of electrochemical method consists of a microreactor and four electrodes. A schematic view of the microsystem is presented on Figure 3. The microreactor's structure is made in form of two chambers divided with a step. In the reaction chamber a catalytic media in form of glass balls of 100 μm diameter is placed on the surface, on which an enzyme is immobilized (urease).

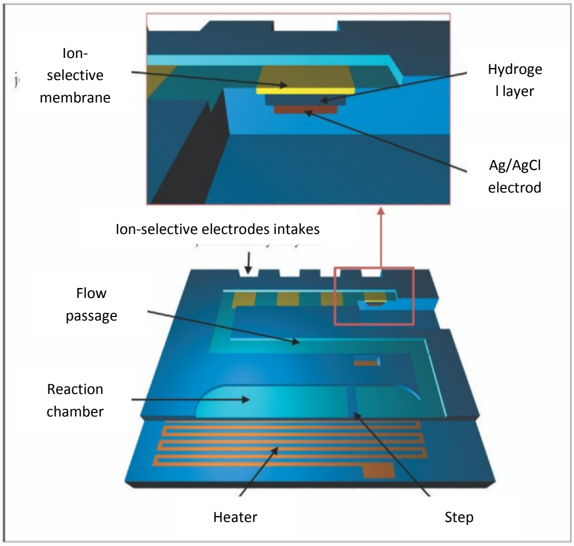


Fig. 3. A schematic view of a microsystem of urea liquid-based determination

The enzyme catalyzes the urea hydrolysis. One of the products of this reaction are ammoniums, concentration of which is potentiometrically determined by means of matrix of electrodes placed at the edge of the system. The rule of potentiometric detection is based on the fact that the electric potential of a properly chosen electrode depends on the composition on the solution, in which it is immersed. Yet, in order to measure the electrode's potential, one must create a cell – in other words connect two electrodes in a proper way. Measuring the electromotive force of such a link, the composition of a given solution might be determined. The measuring cell consists of a measuring electrode, the potential of which depends on the concentration of the determined ion, and a reference electrode, the potential of which is constant and independent of the concentration of the determined ion during the measurements. In case of the described system, as the measuring electrode an Ion Selective Electrode (ISE) was chosen. Such an electrode contains a specially dissected membrane, the interior surface of which touches with a so called internal electrolye (a hydrogel layer). The internal electrolyte contains membrane-sensitive ions and ions maintaining a balance with an output electrode. In addition, a thick-film heater was integrated with this system. Its task was to stabilize the temperature in the whole reaction chamber.

The microsystem was made of seven LTCC layers. The shapes of microreactor chambers and microchannels were cut from a raw ceramics by means of a Nd-YAG laser. Both silver electrodes of potentiometric detector and the heating windings were put with the use of the screen printing method. After the laser cutting and screen printing processes, the ceramic tapes were laminated and co-fired in compliance with standard technological procedures.

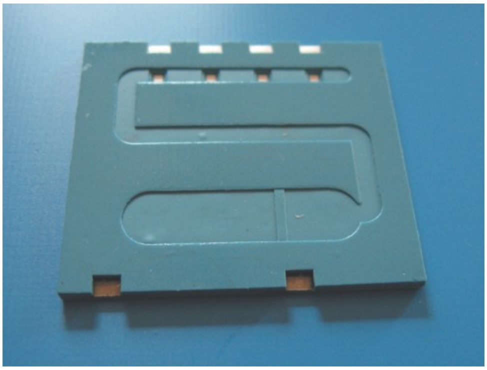


Fig. 4. Microsystem for urea determination made by means of LTCC technique

The given microsystem for urea liquid-based determination was tested in the flow system. The measurements were taken in the room temperature and at the flow rate of 0,6 ml/min. Detector calibration was made for five standard solution concentration values. The analyte concentration changes were increasingly taken each 200 seconds. The measured dynamic response of the LTCC microsystem is shown on Figure 5.

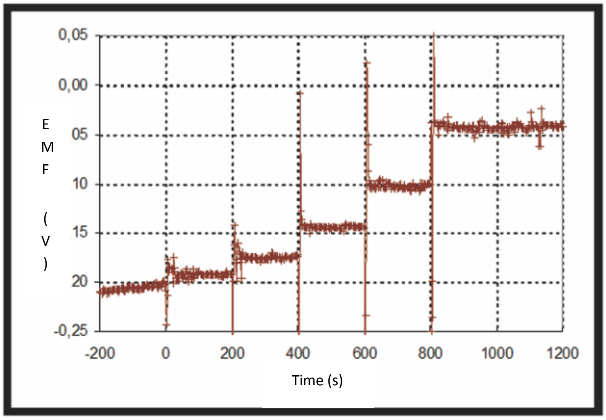


Fig. 5. Dynamic response of the LTCC microsystem for urea determination

The microfluidic system for heavy metal ions water concentration determination is built from ceramic casing, in which an intake channel was made by means of microengineering methods, measuring channel (absorption cell), outtake channel and cavities for optoelectronic elements. A drawing of the microflow system's casing with 3D structures is presented on Figure 6.

The system's operation is based on partial light absorption, generated by a LED (*Light Emitting Diode*), by the analyte flowing through the measuring channel. The unabsorbed light is transmitted by a fibre-optic cable to a photodetector. The amount of light absorbed by the analyte is proportional to its concentration, according to the Beer-Lambert law:

where:

A – optical absorbance,

$$A = -\log\left(\frac{I}{I_0}\right) = \varepsilon \cdot c \cdot l \qquad (1)$$

I_o and I define light intensity before and after the analyte absorption,

c is the analyte concentration (M),

ε is the extinction coefficient ($cm^{-1}M^{-1}$)

l is the optical path length (cm).

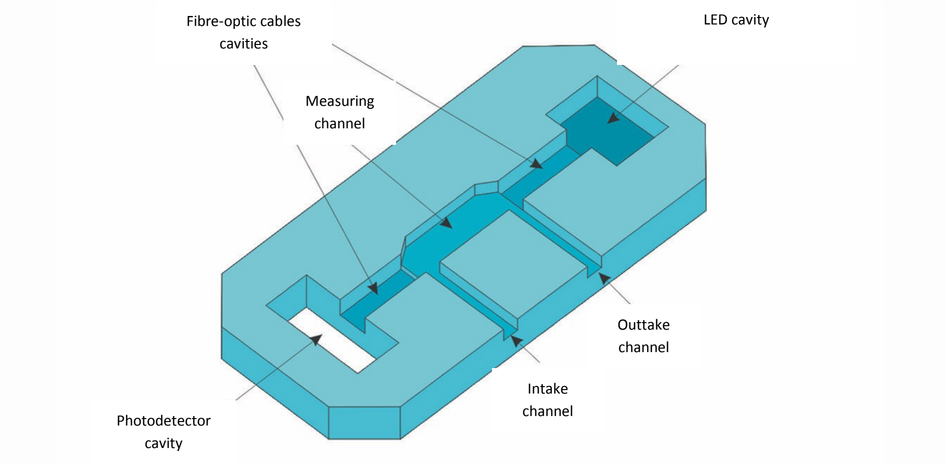


Fig. 6. Microfluidic system casing containing flow passages and cavities for optoelectronic subassemblies

In case of identical measurement values (with set optical path length and constant extinction coefficient), the absorbance value depends only on the concentration of the tested analyte.

Five LTCC layers were used for microfluidic system construction. As in the case of the previously discussed microsystem, the channels and cavities were cut in the raw ceramic tape by means of a laser. On the bottom of the system a network of conductive pathways, enabling LED and photodetector power supply and the output signal reception, was put. Conductive pathways were made of a PdAg grease. The microfluidic system was designed, so that the measurement channel was two tapes lower than the channel for fibre-optic cables (Fig. 7). Due to this solution, the fibre-optic cable blocks automatically before the measuring channel.

After the completion of the laser-cutting and screen printing processes, all tapes were piled in a proper order and laminated in an isostatic press. The produced laminate was then fired in the oven-type furnace in the air atmosphere. The last technological stage dealt with LED, photodetector and two polymer fibre-optic cables installation. The LED, photodetector and all reactors were connected to the LTCC casing by means of a standard soldering method. The polymer fibre-optic cables were inserted into proper channel with the use of epoxy. A view of the microflow system for heavy metal ions water concentration determination after the installation of the optoelectrionic elements and leads is presented on Figure 8.

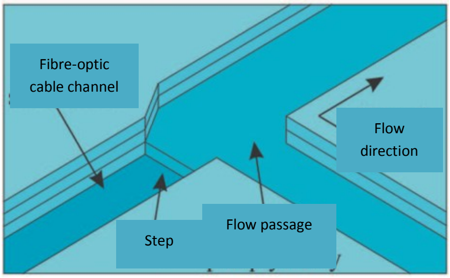


Fig. 7. Microflow system construction enabling accurate fibre-optic cables positioning

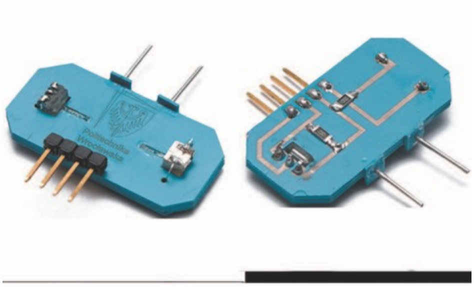


Fig. 8. Microfluidic system for heavy metal ions water concentration determination

The system was tested by means of potassium permanganate water solution of molecular formula $KMnO_4$. The maximum absorption of this chemical compound falls within the range of 500-550 nm wavelength. Several potassium permanganate solutions of concentrations from 9,5 to 158 μM were prepared. Individual concentrations of the test solution were pumped into the microflow system by means of a syringe driver. The analyte in the flow passage was lighted with a green light generated by the LED. The unabsorbed light was transmitted by the fibre-optic cable to the photodetector. The absorbance measurement was taken by the voltmeter on the direct output voltage, taking into consideration the following formula:

$$A = \log\left(\frac{I_{H_2O}}{I_C}\right) = \log\left(\frac{U_{H_2O}}{U_C}\right) \qquad (2)$$

where:
I_{H2O} – intensity of light illuminating the distilled water photodetector,
I_C – intensity of light for the analyte of unknown concentration,
U_{H2O} – distilled water photodetector voltage [V],
U_C – the analyte of unknown concentration photodetector voltage [V].

Figure 9 shows the measured dynamic features of the microfluidic system for five concentrations and for distilled water.

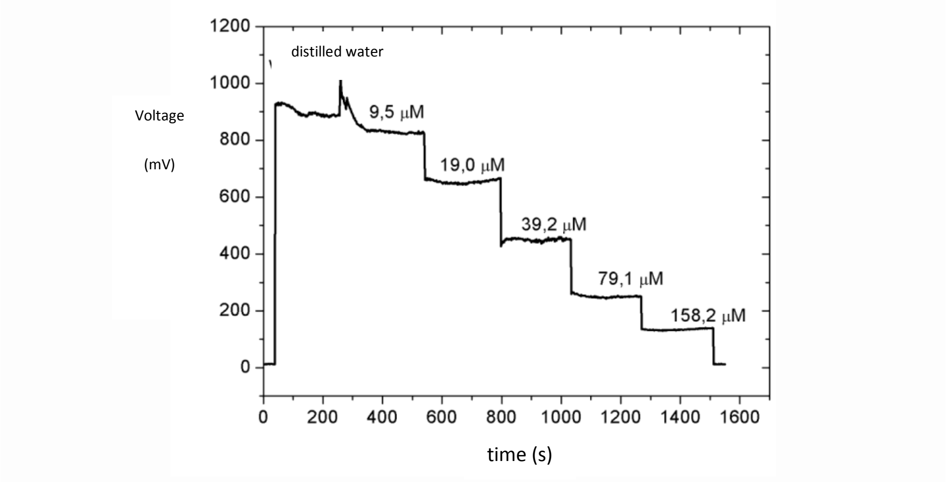


Fig. 9. Dynamic response of the microfluidic system for heavy metal ions determination and for various standard solution's concentrations

Conclusion

Increased interest in researches dealing with the microfluidic systems has been observed in recent years. Such devices are usually produced with the use of modern microengineering methods, characteristic for semiconductor technology (diffusion, implantation, iso- and anisothropic etching). This study elaborates on an alternative method of the microfluidic systems application, by means of a cheaper and simpler technology based on the employment of the LTCC and materials characteristic for thick-film technique.

The LTCC technology was successfully used in constructing stages of the following two model microfluidic systems: the microsystem for urea determination and the system for heavy metal ions water determination. The measurements of electric properties revealed that these systems are very sensitive and their output signal possesses good repeatability-in-time value.

The microfluidic systems made by means of the LTCC technology might be an alternative to the silicon systems, the most commonly used ones at present. They can be applied in: environmental monitoring measurement systems or medical diagnostics personalized bedside systems.

The electrode chemical modification process was performed by PhD Eng Dorota Pijanowska and PhD Eng Marek Dawgul from the Institute of Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences in Warsaw.

Karol Malecha is a grant holder of the START program of the Foundation for Polish Science.

Summary

The paper presents the basic information coping with Low-Temperature Co-fired Ceramics (LTCC) and the microelectronic system production associated with it. An alternative application of the LTCC technique for microfluidic systems creation has been described. The technology, construction and properties of the microsystem for urea determination in fluids and the microfluidic system for detection of heavy metal ions in water determination was elaborated on as well.

Keywords: Low temperature co-fired ceramics, microfluidics, microsystem, thick film.

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Application of TiN coatings in kinematic frictional nodes

Janusz Lubas*

Summary

This work revealed the results of the impact of the formed TiN surface layer and the ring structure of TiN-steel 46Cr2. In the sliding pairs, the counter-samples were made from CuPb30 and AlSn20 bearing alloys and the friction area was lubricated with Lotos 5W/40 oil. The results of the tests proved that the moment of friction at the start-up, friction force and temperature in the friction contact area depend on friction conditions and a combination of the cooperating surface layers. The application of ring structure has a significant influence on the decrease of the wear of bearing alloy.

Keywords: wear, sliding friction, surface treatment, PVD.

1. Introduction

Obtaining the desired level of reliability and strength of a mechatronical product is associated with technical-economic requirements set during the designing stage and parts and construction elements, being its components. Designing such device, one has to connect drive, a set of sensors gathering the information regarding the surroundings, control system based on a microprocessor and software ensuring multifunctionality, flexibility and configurability, as well as a possibility of adaptation to constantly changing conditions [1].

The increase of reliability and strength of the kinematic systems employed in mechatronical products is possible by means of the choice of proper technology of their manufacturing or introduction of new construction solutions. The ones being used at present are characterized by untypical structure of the surface layer, what increases their operation capabilities. The idea of constructing these layers is based on the application of interactions of various materials properties' resultants, accompanied by their

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positioning on the sliding surface, one next to the other [2, 3]. In order to produce such construction, mechanical, thermal-mechanical, thermal-chemical, electrochemical or other mixtures are employed, yet it causes the technological process's elongation and production costs' increase. A significant simplification of the production process of these layers is obtained by PVD methods application. Such methods are used in mechatronics mainly in microelectronical technologies, but there is also a possibility of their application into mechanical systems' elements without increasing their production costs, while improving the tribological properties of the final product.

2. Technological and operating parameters of a kinematic pair

The object of the study is a friction pair described by construction, material and technological preferences. The tests to be realized range from determination of coefficients values associated with this friction pair operation, to elements with TiN coating. The tests, containing bearing material and variable parameters of the friction pair load, will define the areas of effective application of such a solution. The friction pairs destined to the analysis consist of a ring-shaped sample and a counter sample from a plain bearing's sleeve sector (Fig. 1).

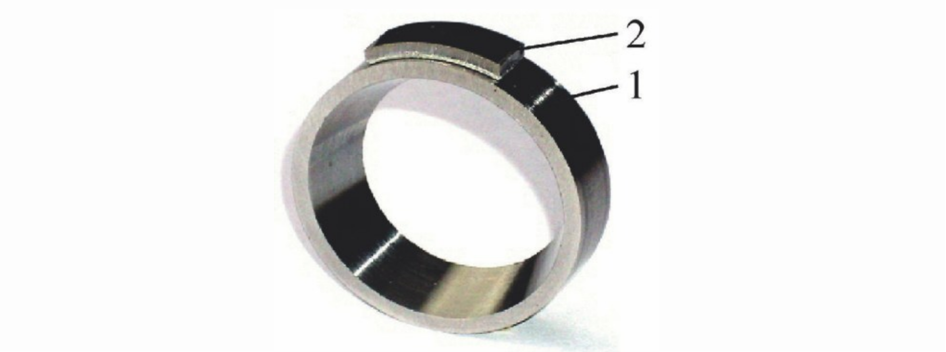

Fig. 1. Friction pair: 1 – ring-shaped sample, 2 – counter sample

The ring samples were made of steel 46Cr2 (0,46% C, 0,5% Cr, 0,65% Mn), and then it was subjected to thermal processing, with the aim of obtaining strength 42±2 HRC, and final processing, shaping the previously set values of length and shape deviations (Fig. 2). Consequently, a process of setting the TiN coating by the PVD method was performed (coating setting time τ=40 minutes, process temperature t=270ºC, pressure in the ionization chamber $p=1{,}2\text{x}10^{-2}$ mbar). During this process, on the ring-shaped sample a homogenous TiN coating and ring structure TiN-46Cr2 were shaped, the latter consisting of alternating rings of the TiN layer and steel ground (46Cr2 steel) (Fig. 2b). The ring samples with shaped surface layers were linked and formed into friction pairs with counter samples made of AlSn20 and CuPb30 bearing alloys, while the friction area was lubricated with Lotos 5W/40 oil.

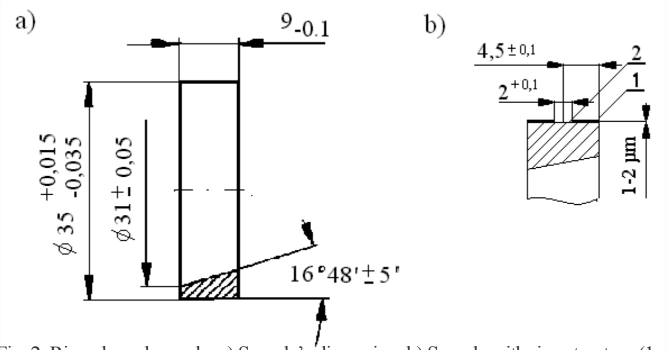

Fig. 2. Ring-shaped sample: a) Sample's dimension, b) Sample with ring structure (1 – TiN coating, sample material 46Cr2)

The site tests were conducted on a roll-block type tester according to the algorithm coping with initial samples run-ins and the proper cooperation process, regarding the previously set load parameters. The run-in process was realized on a test site with a 5 MPa load until the counter bearing alloy sample surface adjoined to the ring sample surface. Then the kinematic pair start-up tests were performed (0 – 500 RPM, 120 seconds, pair stoppage after 30 sec, surface pressure – 15 MPa. What is more, the friction pairs tests were conducted in experimental loads conditions: surface pressure 10, 15, 20 MPa, ring sample speed n=100 RPM. During the tests' real-time, the following coefficients were measured: friction coefficient, start-up moment, friction force, temperature of the friction area and friction pair elements wear and tear within the variable unit pressures function.

3. Friction processes within the friction pair with modified layers

The friction pairs' performance characteristics derive from the physical and geometrical properties of outer layers and their elements. They decide over the type and course of elementary friction and wear phenomena, at the same time influencing the changes in the previously shaped outer layer.

Tab. 1. Friction pair elements surface roughness

Ring	Counter samples	Surface roughness R	
		Ring sample	Counter sample
TiN	CuPb30	0,31	0,33
	AlSn20	0,39	0,35
		Surface/ground roughness	
TiN - steel	CuPb30	0,33/0,26	0,51/1,11
	AlSn20	0,39-0,28	0,53/0,84

R_a roughness paratemetr measurements for ring samples and counter samples, in connection with a homogenous Tin layer, occurred to have similar values of this particular parameter (Table 1). The balance of roughness of both elements is an illustration of shaping an optimal geometrical structure for a given friction pair composition and load conditions. However, in the friction pairs with ring samples of ring structure TiN-46Cr2 there are bands of variable value of the measured R_a parameter. The measurements taken on the counter sample proved twofold increase of surface roughness in the junction area with the ring's ground (46Cr2 steel) in comparison with the junction areas with the previously shaped TiN layer.

The differences in the measured Ra parameter value are the result of disparate friction conditions occurring in the junction areas and caused by other properties of cooperating materials, lubrication conditions and wear products interaction. As a result of the processes undergoing within the friction area and under the influence of outside forces, the tribological system processes the initially existing geometrical structures of both elements into a system of structure ensuring the best possible friction conditions. The effect of these changes is an operating surface layer. The measured high surface roughness of the bearing alloy counter sample within the junction with the ring sample's ground results mainly from the micromachining effect that was arisen by wear products and adhesive injection caused by the increase of temperature within the friction area [4, 5].

Essential factors, having an impact on the friction pair's friction processes, are cooperation conditions of start-up-shaped surface layers and the speed obtained after the period of the initially set working conditions. The record of changing friction resistance in the tested friction pairs does not allow to determine a homogenous description function for all studied associations (Fig. 3).

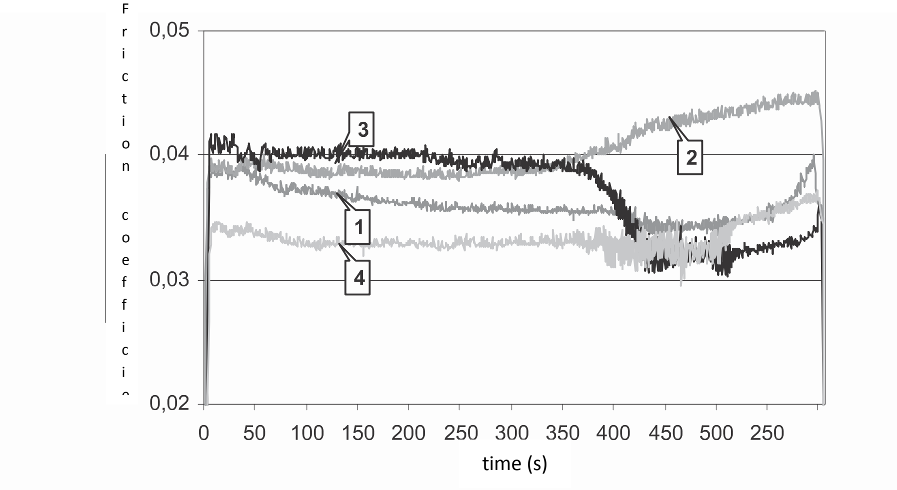

Fig. 3. Friction coefficient change during the start-up and braking of the friction pair:
1-TiN-CuPb30, 2-(TiN-46Cr2)-CuPb30, 3-TiN-AlSn20, 4-(TiN-46Cr2)-AlSn20

As for the friction pairs with the ring sample with the homogenous layer TiN-CuPb30 and the ring sample (TiN-46Cr2)-AlSn20, after the initial high level of friction coefficient value, its decrease and stabilization occur after exceeding 400 RPM. Another increase of friction resistance is generated during the friction pair braking. The pairs differ from each other by the friction coefficient that in TiN-CuPb30 matchings it is considerably higher. In the remaining two pairs the change course of the friction coefficient is stable up to 360 RPM and operates on the 0,04 level. Having exceeded the mentioned value (360 RPM), in the friction pair with the ring sample with the homogenous layer TiN-AlSn20 the decrease of the friction coefficient from 0,04 to 0,032 is very characteristic. On the other hand, in the friction pair with the ring sample (TiN-46Cr2)-CuPb30 the increase of the friction resistance can be noticed and this tendency keeps still also during the friction pair braking.

As far as the working conditions of the friction pair are concerned, the vital issue is also the setting of maximum breakaway torque which determines the friction resistance and the kinematic system energy demand in the very moment of its commissioning.

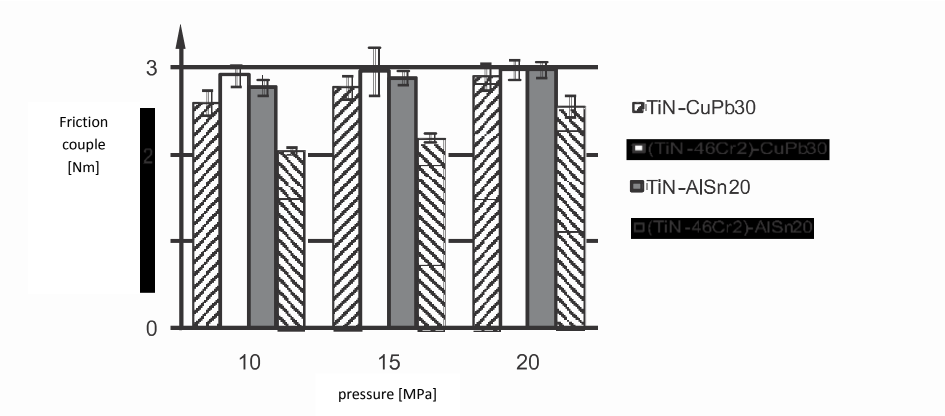

Fig. 4. Maximum friction couple during the friction pair start-up

The breakaway torque measurements proved the tendency of the increase of its value accompanied by the friction pair load increase. The lowest values of the friction couple during the start-up occur in the friction pair (TiN-46Cr2)-AlSn20. In the remaining matchings the value of the measured friction couple are on approximately the same level. The analysis of the results does not allow to make a generalization because in the friction pairs with the alloy counter sample CuPb30 such a matching with the homogenous TiN layer is more positive, yet the distribution of the values between the measured friction couples is relatively slow.

Friction parameters change observation during the start-up reveals the information about the system's functionality in its further operation. The best working conditions occur in the kinematic pairs, in which after the friction coefficient increase in the initial phase of the start-up, it the further stages it will be lowered and stabilized yet again. In such pairs in a given time there is a tribochemical balance. The registered changes are the results of physic-chemical . As for the friction pairs, in which there is a decrease of the friction coefficient, of the improvement of the friction conditions decide the increase of the lubrication effectiveness. The oil layer lubrication effectiveness improvement is shaped by the current friction pair load condition, temperature level and chemical reactions within the friction area. As a result of the chemical composition of the oil and forming of new compounds, a border layer is created. Changing the antiwear layer structure, it causes its strengthening and lowering the motion resistance. In such conditions there is a possibility of processes' within the friction area self-regulation, what may influence the stabilization of the motion resistance, in spite of the ring sample's sliding speed increase. The lack of such self-regulation favors the seizing up process of the friction pair and, finally leads to a failure or breakdown [6, 7].

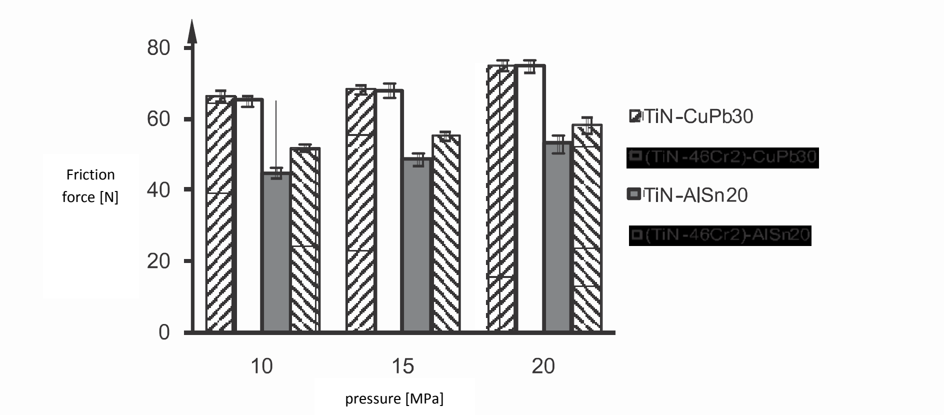

Fig. 5. Friction force in the friction pair depending on the ring sample's shaped surface layer

In the set working conditions of the friction pair, some significant differences in the friction force regarding the employed counter sample materials were observed (Fig. 5). The samples, obtained during the tests, proved that the friction pairs with the counter sample of the AlSn20 alloy are characterized by lower values of the friction force than the pairs with the counter sample of the CuPb30 alloy. In the friction pair with the counter sample of the CuPb30 alloy the measured values of the friction force are similar for both surface layers shaped on the ring samples. On the other hand, in the friction pairs with the counter sample of the AlSn20 alloy, matching with the homogenous TiN coating, the friction force is of a dozen percent lower than that registered with the ring sample with the TiN-46Cr2 band structure.

The temperature measurements in the junction area in the contemporary cooperation conditions showed the changes' similar character to those registered during the friction force measurements. The counter sample of the AlSn20 bearing alloy application in the friction pair causes the significant temperature decrease in the friction area, in comparison with the CuPb30 alloy (Fig. 6). Temperature in the friction pairs with the counter sample from the AlSn20 alloy does not exceed 55ºC together with the unit switch pressure (20MPa), where, analogically, in the matching of the CuPb30 counter sample it exceeds over 85ºC. In the friction pair with the counter sample of the AlSn20 alloy, as during the friction force measurement, the employment of the homogenous TiN coating influenced the decrease of temperature in the friction area even by a dozen or so degrees.

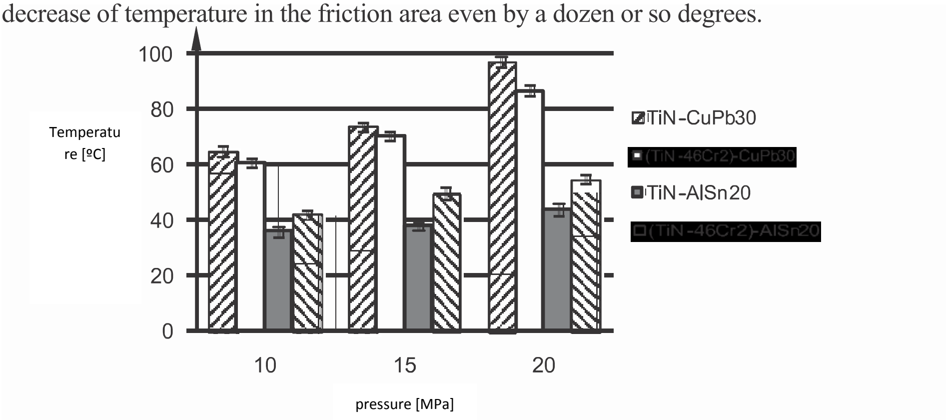

Fig. 6. Friction area temperature, depending on the ring sample's shaped surface layer

On the other hand, in the friction pairs with the counter sample from the CuPb30 alloy lower temperatures with given matchings, in which the ring samples of ring structure TiN-46Cr2 were not produced anymore. In this group of the visible temperature increases, the temperature's perceptible and visible temperature jump regarding its own temperatures measured by the lower layers of the unit pressures.

The parameter values, characterizing the friction pairs' cooperation in the stabilized working conditions, are the result of the surface pressure causing the friction surfaces. The oil layer is being stopped by the cooperating surfaces' performances. The increase of the density of elementary joint surfaces intensifies the destroying process in place of the border lines. The conditions of accumulating and spilling the oil onto the friction surface decrease, border layer strength is lowering, the resistance friction increases, what indirectly influences the temperature increase in the joint area. The above-mentioned changes may lead to a so-called "flashing temperature" [3], what creates a sudden desorption of the oil components and their thermal decomposition. Such processes lead to the elimination of all interlocks and adhesive connections, what generates the increase of friction resistance, temperature increase and material wear and tear and during the final stage it may lead to the calculation of the possibility of the friction pair damaging due to its seizing up (outside forces or emergency wear of the pair elements) [8].

During the tests in the condition of previously set loads, linear wear and tear of the friction pair elements was also measured (Fig. 7). The ring samples measurements did not point out to any measurable wear, yet the wear of the bearing alloy counter samples

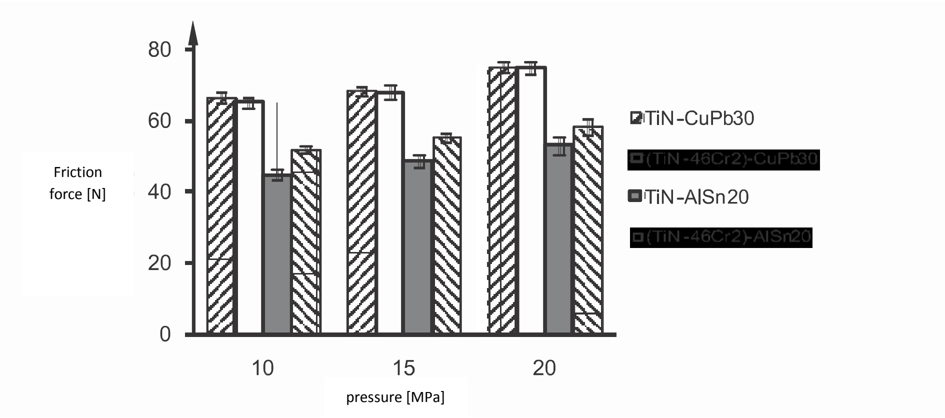

Fig. 7. The wear of the counter sample material

was registered. The results showed a considerable influence of the surface layers' shapes and the cooperative ring samples. The application of the TiN-46Cr2 ring structure causes the bearing alloy wear to be smaller of more than a dozen percent in comparison with the friction pairs, in which the ring samples with the homogenous TiN layer were implemented. The measurement results pointed out to significantly lesser wear of the counter sample of the CuPb30 alloy, compared to the counter sample of the AlSn20 alloy. The total wear value of the counter sample of the CuPb30 alloy does not exceed 0,14 mm, while the AlSn20 one's reaches up to 0,18 mm (by the unit pressures of 20 MPa).

The differences in wear and tear values of the bearing alloys and the lack of measurable wear of the ring samples with technological surface layers are all the result of the considerable difference of strength between the individual friction elements, the mutual interactions of cooperating surface layers, as well as the physicochemical phenomena occurring on their surfaces, being the results of the outside forces. Such phenomena derive from the course of elementary wear processes within the junction area of the friction pair, the interaction of the lubrication factor which – undergoing constant changes – generates boundary layers of high stoppage resistance on the previously formed surface layers , or, on the other hand, is destroyed by constantly changing working conditions. In the cooperation conditions, the secondary phenomena of the wear and friction processes occur as well: the interaction of isolated wear particles into the cutting surface layers, transportation of the material particles from one element to the other, electron emission and corrosion current flow. Moreover, in the sliding friction conditions, apart from the lubrication factor's presence, the oxidation processes occur as well. They cause the creation of oxides on the surface layer of the cooperating friction pair elements. The created oxides lead to the decrease of the friction and wear coefficient in the friction processes, but in the unfavorable friction conditions with matching with hard and brittle surface layers they bring on the increased wear of the counter sample material of lesser strength [3, 6, 9].

Conclusion

On the basis of the experiments and analysis of their results, one may propose the following lid:

1. The employed technology enables the friction pairs production with durable surface layers of tribological properties, required in the friction pairs operating in the sliding friction conditions.
2. A vital increase of the surface roughness occurred on the counter samples of the bearing alloys with mechanism of the ring structure in the cooperation band with the sample ground, while in the junction areas with the TiN layer the surface geometry is similar to the one obtained by means of the matching with the homogenous TiN layer.
3. In the tested matchings the employment of the AlSn20 bearing alloy decreases both the friction resistance during the friction pair start-up, and the friction force and temperature within the friction area in comparison with the CuPb30 bearing alloy.
4. It has been proved that the wear of the bearing alloy is lower than the matchings with the ring structure and, yet, the measured ring samples wear and tear was not registered.
5. The employment of the AlSn20 alloy bearing in the friction pair cause the significant increase of its wear and tear, in comparison with the CuPb30 alloy.

Summary

This study presents research results of the shaped surface layer TiN and the ring structure TiN-steel 46Cr2 influence on the friction pair operation. In the friction pairs the counter samples were made from the bearing alloys CuPb3- and AlSn20, while the friction area was lubricated with the Lotos 5W/40 (a cheap one – potentially). The results have proved that the breakaway torque, friction force and temperature within the friction area depend on the friction conditions and combination of cooperating surface layers. The application of the ring layer significantly influences on the lesser wear and tear of the bearing alloy.

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