POLITECHNIKA LUBELSKA

MONOGRAFIE

Robotics and manufacturing systems

edited by

Lucia Koukolová

Antoni Świć

Lublin 2014

Robotics and manufacturing systems

Monografie – Politechnika Lubelska

Politechnika Lubelska
Wydział Mechaniczny
ul. Nadbystrzycka 36
20-618 LUBLIN

Robotics and manufacturing systems

edited by
Lucia Koukolová
Antoni Świć

Politechnika Lubelska
Lublin 2014

Conference proceedings – International Conference
„Robotics and Manufacturing Systems 2014“

Reviewers:
Prof. D.Sc. Eng. Mikuláš Hajduk
Assoc. Prof., D.Sc. Eng. Marek Janczarek

Scientific committee:
Prof. D.Sc. Eng. Antoni Świć - Chairman of the Scientific Committee
Prof. D.Sc. Mikuláš Hajduk
Prof. D.Sc. Grzegorz Litak
Assoc. Prof., D.Sc. Eng. Tadeusz Nieszporek
Assoc. Prof., D.Sc., Eng. Jerzy Stamirowski,
Ph.D. Eng. Arkadiusz Gola
Ph.D. Eng. Jarosław Zubrzycki
Doc. Eng. František Novotný, CSc.
Doc. Eng. Marek Sukop, PhD.
Doc. Eng. Ján Semjon, PhD.

Typesetting: Katarzyna Piotrowska, Łukasz Sobaszek

Photograph at the cover: Łukasz Sobaszek

Publication approved by the Rector of Lublin University of Technology

ISBN: 978-83-7947-104-1

Publisher: Lublin University of Technology
ul. Nadbystrzycka 38D, 20-618 Lublin, Poland
Realization: Lublin University of Technology Library
ul. Nadbystrzycka 36A, 20-618 Lublin, Poland
tel. (81) 538-46-59, email: wydawca@pollub.pl
www.biblioteka.pollub.pl
Printed by : TOP Agencja Reklamowa Agnieszka Łuczak
www.agencjatop.pl

Impression: 100 copies

CONTENTS

Mikuláš Hajduk[1]

METHODOLOGICAL FRAMEWORK OF THE DESIGN OF MULTIROBOTIC CELLS

1. INTRODUCTION

In the last period it can be observed significant changes in the development of robotics [1,6,8]. Although at present the development of robotic is focused on service robotic nevertheless also in the area of industrial robots can observe a significant shift in their aplications [7,9]. While the configurations of industrial robots are stabilized, their parameters and possibilities of utilization are significantly expanding. The one area of the building multirobotic systems are multirobotic cells [2,4]. The multirobotic cells represent the concept of workplace with multiple robots whose activities are coordinated. Even now there were build robotic workplaces with multiple robots, but their activities were autonomous without the possibility of mutual coordination or substitution [5]. It seems that increased effect of multirobotic cells can be achieved by coordination and cooperation of multiple robots to perform the same tasks or operation. A lot of multirobotic cells are created especially for spot welding of the body of the car, arc welding and assembly. Handling of multiple robots with the same object is considered as latest and rapidly evolving multirobotic cells. In this area there is created a lot of hybrid multirobotic cells where cooperates industrial and service robots [3].

The paper is focused only on the methodological framework of the design of multirobotic cells with industrial robot. The proposed methodological framework may be useful not only for profilation of new workplaces, but also for re-profilation of existing workplaces, which can then achieve a high degree of robotization of technology operations but also robotic manipulation.

[1] Technical University of Kosice, Faculty of Mechaical Engineering, Departemnt of Robotics, B. Nemcovej 32, Kosice, Slovakia, e-mail: mikulas.hajduk@tuke.sk

2. PROPOSAL OF THE APROACH TO THE DESIGN OF MULTIROBOTIC CELLS

The potential of effective solutions of the production can be found in the utilization of multiple robots in one workplace or in utilization of multiple cooperative robots for performing common tasks, figure 1. It is a widely variant aproach in which it is possible to use many aproaches of profiling methodology of workplaces with one robot but there is also created a number of new solutions such as assessment of operations for the implementation of multiple robots, distribution of operations for individual robots, determination of the number of the robots and many other.

Because multirobotic systems are relatively new concept of robotic cells, there are still just few comprehensive methodological aproaches of their design. Based on the wider utilization of multirobotic systems, lessons learned from the design and operation of multirobotic cells are continuously growing and there are formed theories and methodologies for their optimal design.

Basic criteria important for multirobotic cells profilation are:

- maximal shortening of the cell cycle time,
- cooperation of robots and interchangeability of their tasks,
- number of robots minimalization.

Issues to be addressed in the profilation stage of multirobotic cells are: how many robots are needed respectively how many robots can be installed, which type of robots can be assigned to the cell and many others issues.

In the initial step there the weldment and its parts is analysed. Then the location and orientation of the robot accessibility is determined. On this basis the positioning and clamping points are determined. Then the necessary fixture is designed. In the next step there is performed the spatial and time analysis of the operation. Subsequently each operation is assigned to the robot and the number of the robot is set. The assumptions in assessing operations to the robots are:

- each robot is equiped with only one effector respectively technological head (burner, spot ticks) that means the robot performs only exactly assigned tasks,
- some robots can be equiped with removable system of effectors that means the robot can perform more operations,
- some robots are interchangeable with removable system of effector or without removable system that means they can perform operations of other robots. In this case it is apropriate to use the same model of the robot.

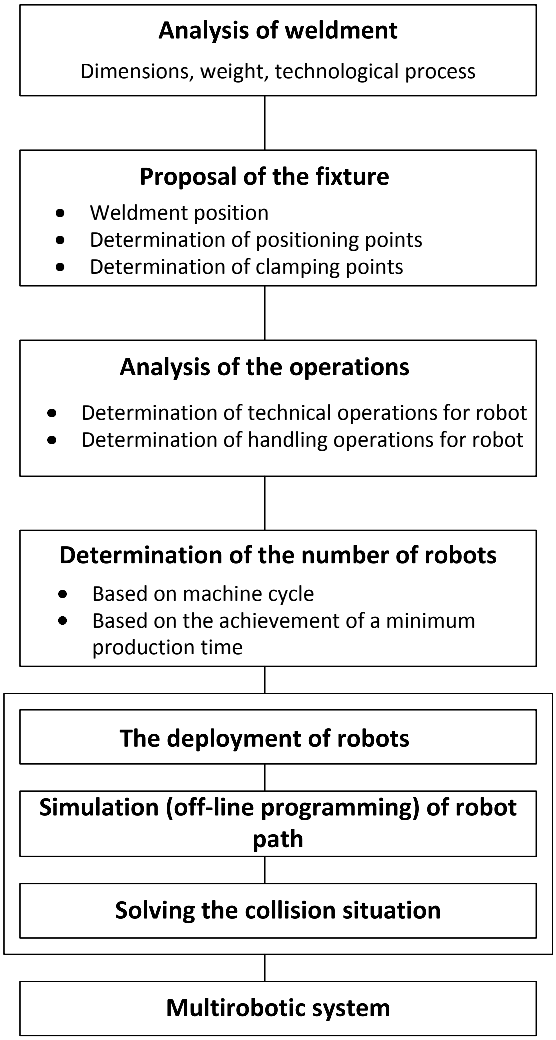


Fig. 1. Methodology of multirobotic system profilation [source: own study]

Important phase in the profilation of multirobotic systems is the design of the robot layout and off-line path planning of robots with the identification of critical situations. Based on these results the proposal of multirobotic system is updated several times until it will reach its optimal structure. Here are a number of possible variants of workplace from which the final variant is chosen. Final variant is selected on the basis of meeting the required criteria.

3. CONCLUSIONS

Multirobotic systems represent a new trend in automation of production. It is no longer a workplace without mutual cooperation of robots based on mutual coordination but it is a workplace with different types of robots and they mutually execute coordinated activities. Such systems bring effects in the implementation of number of operations at the one place and short production time.

Acknowledgements

This paper is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multi-robotic systems".

REFERENCES

[1] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*. [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[2] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning*. Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[3] MIKOLAJCZYK T. et al.: *Multipurpose Mobile Robot*, Aplied Mechanics and Materials, vol. 282, (2013), p. 152–157.

[4] PIOTROWSKI A.: *The Spectacle of Architectural Discourses*, at Architectural Theory Review, (13:2, Routledge, 2008), p. 130–144.

[5] SEMJON J. et al.: *Modular Welding Fixtures for Robotic Cells*, Aplied Mechanics and Materials, vol. 309, 2013, p. 80–87.

[6] ŚWIĆ A., GOLA A.: *Elements of Design of Production Systems – Methodology of Machine Tool Selection in Casing-Class FMS.* Management and Production Engineering Review, vol. 1, no. 2, 2010, p. 73–81.

[7] ŚWIĆ A., WOŁOS D., ZUBRZYCKI J, OPIELAK M, GOLA A., TARANENKO V.: *Accuracy Control in the Machining of Low Rigidity Shafts.* Aplied Mechanics and Materials. vol. 613, 2014, p. 357–367.

[8] VAGAS M. et al.: *The view to the current state of robotics*, Advanced Materials Research, vol. 463–464, 2012, p. 1711–1714.

[9] ZUBRZYCKI J., ŚWIĆ A., TARANENKO V.: *Mathematical model of the hole drilling process and typical automated process for designing hole drilling operations.* Aplied Mechanics and Materials, vol. 282 (2013), p. 221–229.

Vladimír Baláž[1]

PRINCIPLES OF PROGRAMMING MULTIROBOTIC SYSTEMS MOTOMAN

1. INTRODUCTION

Control system for robot Motoman NX100 can be configured to control multiple manipulators or stations simultaneously with a single controller [11]. With the independent/coordinated control function, manipulators and/or stations can be operated together or individually [1, 4, 9]. Operation can be optimized for the jobs [2, 3, 7]. Using two coordinated manipulators to execute a job show figure.1. A jigless system is a system that welds by coordinating two manipulators; one holding the workpiece while the other holds the torch [8]. To coordinate the movements of the two manipulators, a coordinated job is needed. In a coordinated job, there is a coordinated operation where two manipulators, master and slave, perform a reciprocal movement, and an individual operation where each of the two manipulators performs an independent movement [5, 6, 10]. A move instruction in coordinated jobs displays two lines. The first line is for the slave side (welding head) and the second line is for the master side (workpiece).

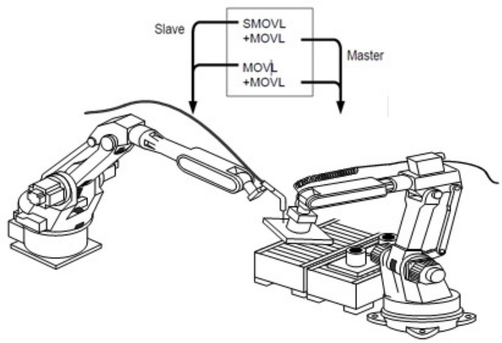


Fig. 1. Coordinated control robots (jigless system)
[source: own study]

[1] Technická Univerzita v Košiciach, Katedra Robotiky, e-mail: vladimir.balaz@tuke.sk

In a jigless system, the control point of slave side manipulator can be set as a reference point so that the master side manipulator can be moved.

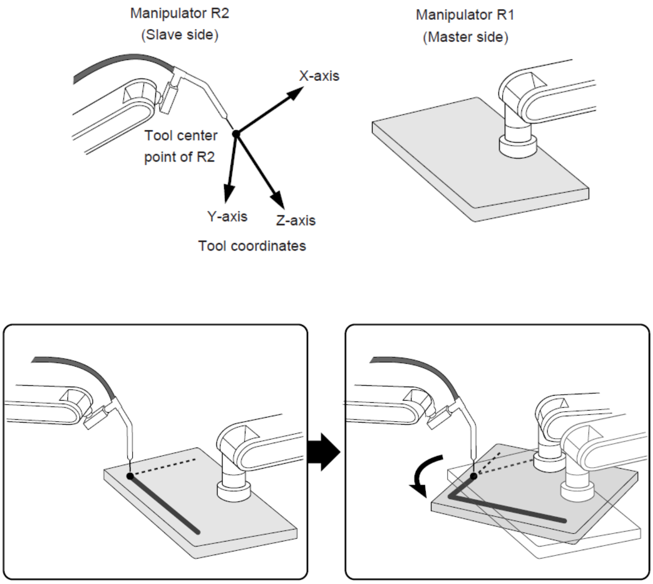


Fig. 2. Example of movement cooperation robots [source: own study]

With this function, manipulators and/or stations execute jobs independently without synchronization. While executing a work job at one station, the other station executes a job to return to the home position for the next job, Fig.3.

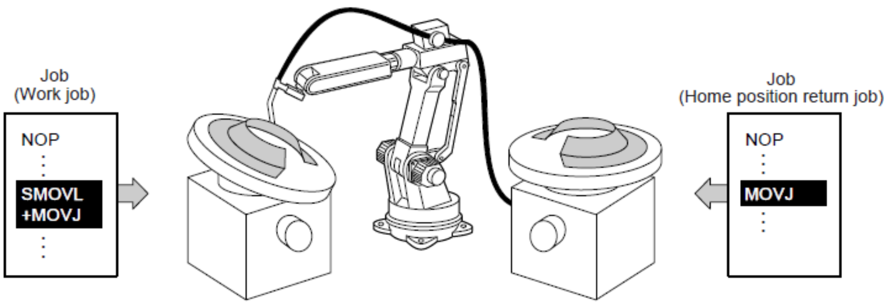


Fig. 3. Independent control [source: own study]

2. INDEPENDENT/COORDINATED CONTROL FUNCTION

The NX100/NXC100 is configured to be able to decode and execute four jobs (with option, maximum eight jobs) each independently. A multitask control performed by this mechanism is called “independent control.” Four mechanisms which execute jobs are called as follows:

Master task
Subtask 1
Subtask 2
Subtask 3

The subtask1, subtask 2, and subtask3 are the tasks to execute jobs that are started by the master task. A job which is able to use move instructions is called a robot job. A job which does not use a move instruction is called a concurrent job, Fig.4.

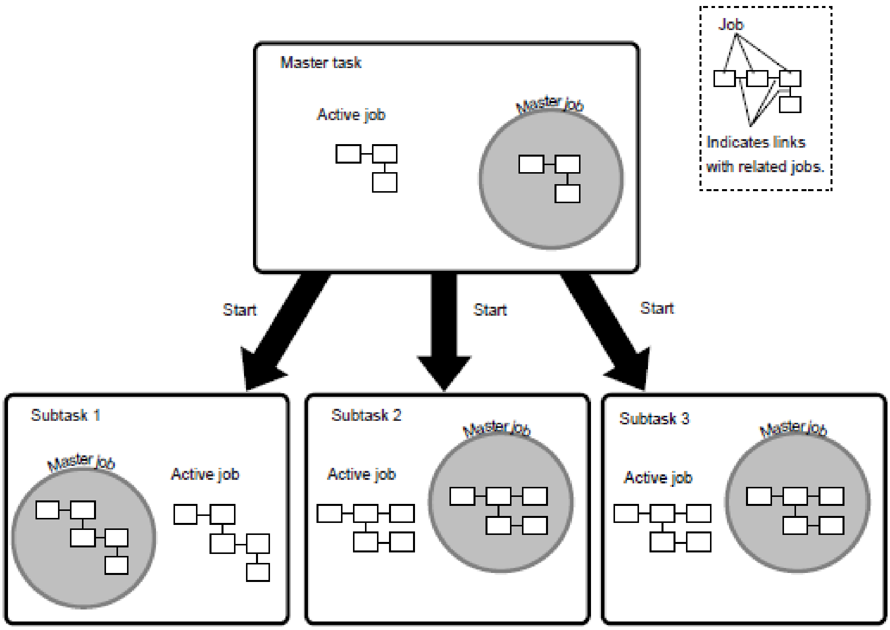


Fig. 4. Master task and subtask [source: own study]

The functions allow programming of cooperative tasks for multiple robots (Motoman) and positioning devices are show on next lines.

SMOVL	While coordinating the slave side with master side, SMOVL moves the slave side manipulator to teaching position. This is a coordinated move instruction to the slave side instruction.
SMOVC	While coordinating the slave side with master side, SMOVC moves the slave side manipulator to teaching position with circular interpolation. This is a coordinated move instruction to the slave side instruction.
SIMOV	While coordinating the slave side with master side, SIMOV moves the slave side manipulator to teaching position by only the specified increment with linear interpolation.
SREFP	During coordinated movement, SREFP specifies a reference point such as wall point fot weaving. This is a reference point instruction to the slave side manipulator.
+MOVJ	+MOVJ moves the master side manipulator to the teaching position with joint interpolation. This instruction should always be placed after a coordinated move instruction (individual interpolation). This is a coordinated move instruction to the master side manipulator.
+MOVL	+MOVL moves the master side manipulator to the teaching position with linear interpolation. This instruction should always be placed after a coordinated move instruction (individual interpolation). This is a coordinated move instruction to the master side manipulator.
+IMOV	+IMOV moves the master side manipulator by only increment with linear interpolation.
PSTART	This instruction starts a job.
PWAIT	This instruction waits for completion of subtask.
TSYNC	This instruction synchronizes different tasks.

3. CONCLUSIONS

Deployment of industrial robots in production often leads to their cooperation. This leads to a reduction in operating time and increase in production. The programming of robots cooperation, managing industrial robot Motoman special set of instructions Independent/Coordinated Control Function. These instructions make it easy the programming of industrial robots Motoman.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multirobotic systems".

REFERENCES

[1] BALÁŽ V., HAJDUK. M., VAGAŠ M., SEMJON J.: *Vytváranie 3D modelov pre CAD systémy off-line programovania robotov*. Robotics and Intelligent Manufacturing Systems: zborník príspevkov z medzinárodnej konferencie: Košice, TU, 2013, p. 51–55.

[2] GOLA A., SOBASZEK Ł.: *Simulation of production flow using Matlab system.* [in:] Lipski J., Świć A., *Optimization of production processes,* Wyd. Politechniki Lubelskiej, Lublin, 2013, p. 64–74.

[3] KOZŁOWSKI E., GOLA A., ŚWIĆ A.: *Model of Production Control in Just-in-Time Delivery System Conditions*. Advances in Manufacturing Science and Technology, vol. 38, no. 1, 2014, p. 77–88.

[4] MIKOLAJCZYK T. et al.: *Multipurpose Mobile Robot*. Applied Mechanics and Materials, vol. 282, (2013), p. 152–157.

[5] NOVOTNÝ, F. HORÁK, M.: *Computer modeling of suction cup sused for Windows cleaning robot and automatic handling of glass sheets*. MM Prumyslove spektrum – MM Science Journ., 2009, p. 113–116.

[6] PIOTROWSKI A., NIESZPOREK T., BORAL P.: *DP in a dispersed control system, management and control of manufacturing process*. Lublin, 2011.

[7] ŚWIĆ A., GOLA A.: *Economic Analysis of Casing Parts Production in a Flexible Manufacturing System*. Actual Problems of Economics, no. 3 (141) 2013, p. 526–533.

[8] YAHUI GAN, XIANZHONG DAI, DONGWEI LI: *Off-Line Programming Techniques for Multirobot Cooperation System*. International Journal of Advanced Robotic Systems, 2013, vol. 10, p. 282.

[9] ZENGXI PAN et al.: *Recent progress on programming methods for industrial robots*. Robotics and Computer-Integrated Manufacturing, 2012.

[10] ZUBRZYCKI J., ŚWIĆ A., TARANENKO V.: *Mathematical model of the hole drilling process and typical automated process for designing hole drilling operations*. Applied Mechanics and Materials, vol. 282 (2013), p. 221–229.

[11] NX100 Independent – *Coordinated Control Function Manual.pdf*

Rudolf Jánoš[1]

METHODOLOGY OF TECHNICAL SCENARIO FOR MULTIROBOTIC CELL

1. INTRODUCTION

Use of multirobotics systems concept in current market conditions attractive, but particularly effective way of successful operation in the market [1,8]. From the perspective of the users of modular robotics is a big advantage the possibility of compiling an accurate design a robot for a given task [2,4,5,9]. An important feature when designing a technical device is a systemic approach [3,6,10]. This means that the robotic device down into basic elements and examining their properties, relations and bonds can create such a device which will ensure compliance with the required functions.

2. SCENARIO FOR THE MULTIROBOTIC CELL

Methodology of scenario – systemic and methodological tool for the preparation stage, request clarification and technical solution is added to the prognostic methods of system modeling method, the object system is broken down into elements with the specified causalities and interaction. Chronologically advises anticipated events or development courses related to forecasting facility with direct causal link to the connection [7].

The product output is based on the key information about the technical challenges multirobotics cell in a given task; Technical specification of performance and output quality.

Process, organizational and duty cycle, the technical specification of the operating cycle, organizational and operational security task implementation; specification of security risks of potential collisions and critical context, the specification of the behavior of robots by the task.

[1] Technical University of Kosice, Faculty of Mechanical Engineering,
Department of Robotics, Nemcovej 32, 042 00 Kosice, Slovak Republic,
e-mail: rudolf.janos@tuke.sk

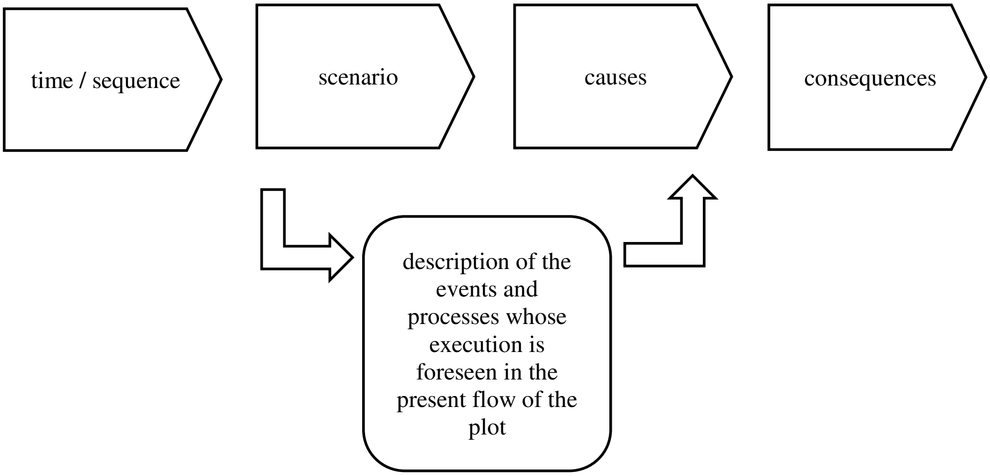


Fig. 1. Sequence of scenario [source: own study]

3. A PRACTICAL APPROACH TO THE IMPLEMENTATION METHODOLOGY TECHNICAL SCENARIO

Technology, technical specification technology specification of technological equipment and installation conditions, descriptions and technical specifications necessary restrictions.

Environment, depending on the operating specification multifactorial, working environment, standardized environmental factors, the specification of the operational environment; specification of the spatial arrangement and layout as well as its structuring; specification of the necessary restrictions.

Client description taken in view of the possibility to operate and use robotic cells, technical specification operation (staff, service, maintenance) options; description of the frequency and program robots using.

Operator, technical specification of the interface interaction operator and robot / environment applications of robots; description of options. Detailed have to be seen in the diagram in Figure 2.

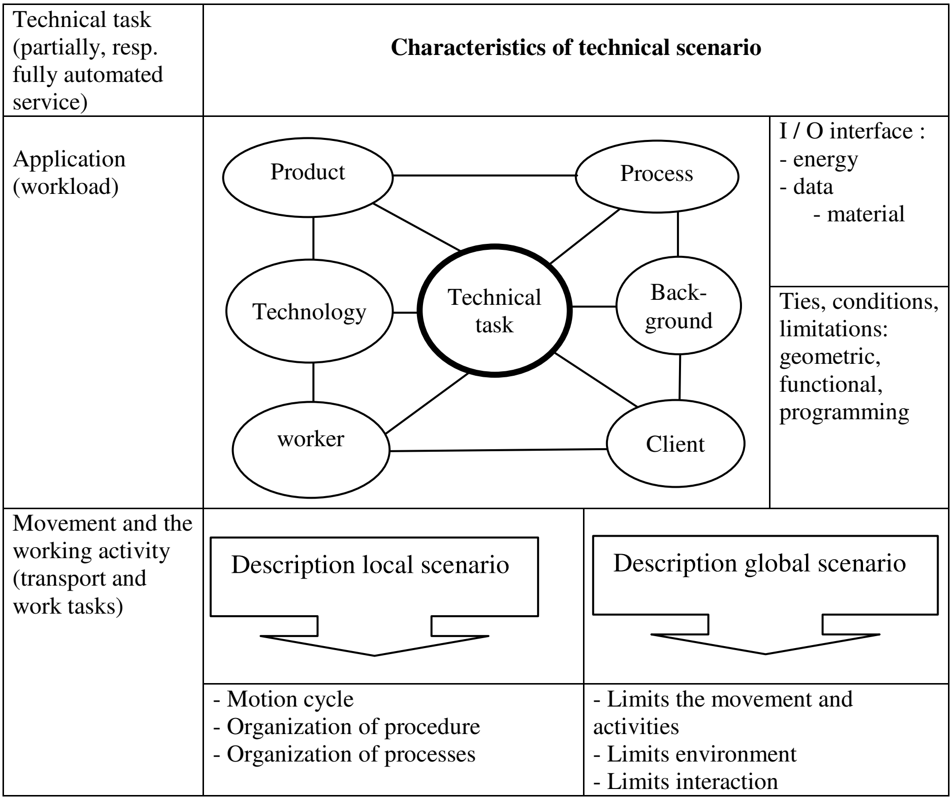


Fig. 2. Diagram of technical scenario [source: own study]

4. CONCLUSIONS

The methodology practices from multirobotic cells task procedure describes the application of the problem in the complex role of the input-output description of the steps and operations and the time series in the specified area and specified the conditions of implementation.

Acknowledgements

This contribution is the result of the project implementation: VEGA 1/0810/11 "Principles of profilation and cooperation of multirobotic systems."

REFERENCES

[1] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*. [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[2] JANTAPREMJIT P., AUSTIN D.: *Design of a modular Self-Reconfigurable Robot.* Cannbera 2005.

[3] MIKOLAJCZYK T.: *Manufacturing Using Robot*. Advanced Materials Research, vol. 463–464, (2012), p. 1643–1646.

[4] MIKOLAJCZYK T.: The *Robot Machining System with Surface Shape Active Control.* OPTIROB'2007, Predeal Romania, University "POLITEHNICA" of Bucharest, p. 205–209.

[5] PIOTROWSKI A.: *The Spectacle of Architectural Discourses*, at Architectural Theory Review, (13:2, Routledge, 2008), p. 130–144.

[6] RUS D., BUTLER Z., KOTAY K., VONA M.: *Self-recofiguring robots.* Communications of the ACM, 45(3), 2002.

[7] SMRČEK J.: *Problem of Metamorphic Structures in Service Robotics.* MM Science Journal, ISSN 1212-2572, Vol. 2, N0 june/2008, MM publishing Praha, Praha 2008 (Czech), p. 16–17.

[8] ŚWIĆ A., GOLA A.: *Elements of Design of Production Systems – Methodology of Machine Tool Selection in Casing-Class FMS.* Management and Production Engineering Review, vol. 1, no. 2, 2010, p. 73–81.

[9] ŚWIĆ A., WOŁOS D., ZUBRZYCKI J., OPIELAK M., GOLA A., TARANENKO V.: *Accuracy Control in the Machining of Low Rigidity Shafts,* Applied Mechanics and Materials, vol. 613, 2014, p. 357–367.

[10] YU C. H. et al.: *Self-organizing Environmentally adaptive Shapes on a Modular Robot.* Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2007, p. 2353–2360.

Frantisek Durovsky[1]

DEVELOPMENT OF LADDER CLIMBING ROBOT

1. INTRODUCTION

Thousands of different robotic constructions have already been built all over the world but only few of them were able to perform vertical ladder climbing. Although to climb a ladder is not considered complicated task for human, it's a real challenge to build such a mechanism. For future outdoor applications, it will be necessary to develop robots which have both high mobility and high work ability [2]. These robots will be required to assist human tasks or to work instead of humans in dangerous sites, disaster areas, mine files etc. [8,15]. There is also demand for robots able to perform inspection tasks on bridges, tunnels or subways [7]. All these fields have rough and complicated terrain with frequent occurrence of various ladders. For wheel or crawler mechanisms it is almost impossible to overcome such an obstacle, even if some jumping robot concepts have already been successfully realized [11,13]. One way or other, legged robots will always have higher terrain adaptability than wheeled ones [10]. If robot is provided with ability to move in various environments, the application fields of this robot will be expanded. Several interesting climbing robots exist already. For inspection of exterior walls of buildings and highway overpasses, quadruped wall climbing robots have been already developed [4, 5]. These robots use sucking disks and are suitable for moving on flat walls and ceilings. However they are difficult to move on irregular surfaces such as wire gauzes and ladders. „Woody robot" developed by Japanese scientists is able to climb tree and support forestry works [9], the rock-net climbing robot is designed to investigate detailed rock mass conditions to predict possibilities of landslides [9] and there are also another robots which can climb a ladder [1, 6].

In long term horizon, robots are expected to work in heights instead of human. Ladders are commonly used in many environments which often require frequent maintenance and inspections such as plants, bridges and factories [3, 14]. To adapt current robots to such complex scenarios, robots which have high mobility, sufficient work ability and acceptable price will be needed.

[1] Technical University Kosice, Department of Robotics, email: frantisek.durovsky.2@tuke.sk

2. MECHANICAL CONSTRUCTION

As mentioned in the beginning, our goal was to build a low-cost service robot able to climb up and down the standpipe chimney ladder located near our university. Step distance of this ladder, was 43±2cm so in order to allow natural human like climbing, the robot length had to overcome distance of two steps. In other words, robot standing on first step, adhering to second step, needed to reach third step by hand to perform successful upclimb. The whole robot design was adapted to this three steps basic assumption and resulted in more than 1m robot length. Mechanical construction was based on well-known robot assembly kit Bioloid, which has already proven to be robust enough for such a development tasks and has helped to significantly reduce time required for mechanical and electronic assembly. Both arms and legs consisted of 5 AX-12 actuators linked together by composite frame system parts as shown in figure 1.

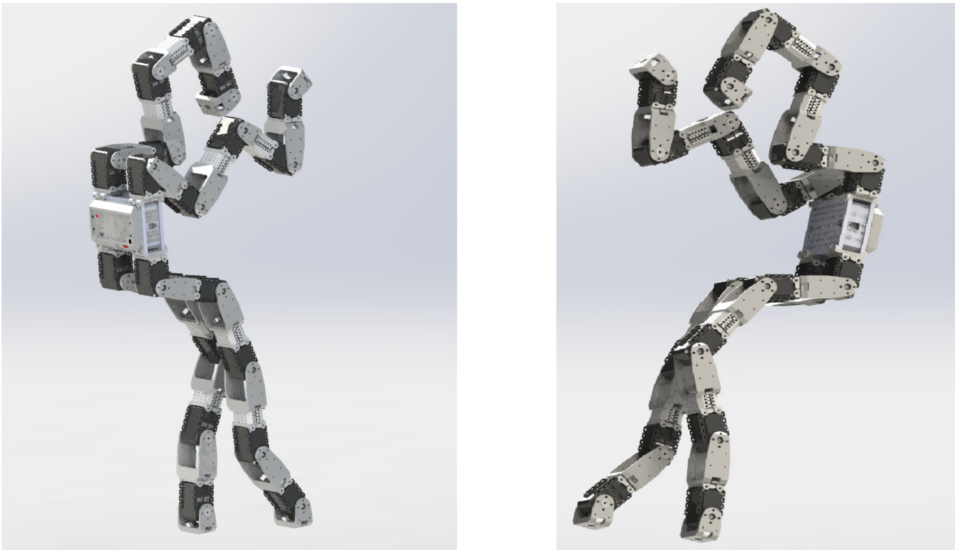


Fig. 1. Basic mechanical construction utilizing Bioloid components [source: own study]

Hook shaped end effectors were custom made and adapted to our ladder steps profile. In result, 5 joint configuration of each arm or leg allowed movement in two axes (forward and vertical) with horizontal rotation axis of each joint. Such a configuration has been accepted as optimal solution according to power and torque limitations of AX-12 modules. But on the other hand the possibility to control each limb movement in all three axes would be helpful in particular climbing situations.

3. CONTROL

In order to simplify the construction as much as possible, we decided not to use any additional sensors such as proximity modules, mini-switches or gyroscopes in the control loop and we rather focused on robustness of moving sequences. The easiest and most convenient way how to control 20 Bioloid actuators simultaneously was to use Robot Operating System [12]. "*dynamixel_ motor*" package available within ROS provides drivers and all important software required for full access to actuators including position, speed and torque control for each particular joint directly from code. Ubuntu 12.04 LTS distribution with full install of ROS Hydro was used. Signals for particular actuators were continuously generated by C++ code on PC side communicating with robot over the wire using USB2Dynamixel interface at 57142 baud rate. No software was downloaded into robot's control unit, as typical for basic Bioloid usage.

Timing and movement synchronization is crucial factor of control since there are several critical robot poses during climbing process which need to be due to torque limitations of AX-12 completed as fast as possible.

4. ELECTRONICS

Robot is powered by 12V DC adapter over the wire. It is also possible to use battery instead, but due to high current consumption and additional load applied to mechanics it is not recommended in this phase of development.

Bioloid actuators use three core cables for both powering and communication. As shown during our experiments, it is not sufficient to provide simple branching wiring (4 wire lines coming from the base), since high current consumption for example in third joint causes voltage drop in following joints (4,5) resulting in module reset. Therefore it is necessary to provide circuit wiring, by linking last right limb joint with last left limb joint together (Fig.2). Circuit wiring provides much reliable communication and power supply since each actuator is connected from both sides.

Data communication is handled by separated cable connected directly to robot control module. Control module in our case works only as a signal and power distributor and robot is completely controlled by PC side. USB2Dynamixel provides USB to 5V TTL logic interface. It is also possible to use wireless connection via ZigBee modules if needed.

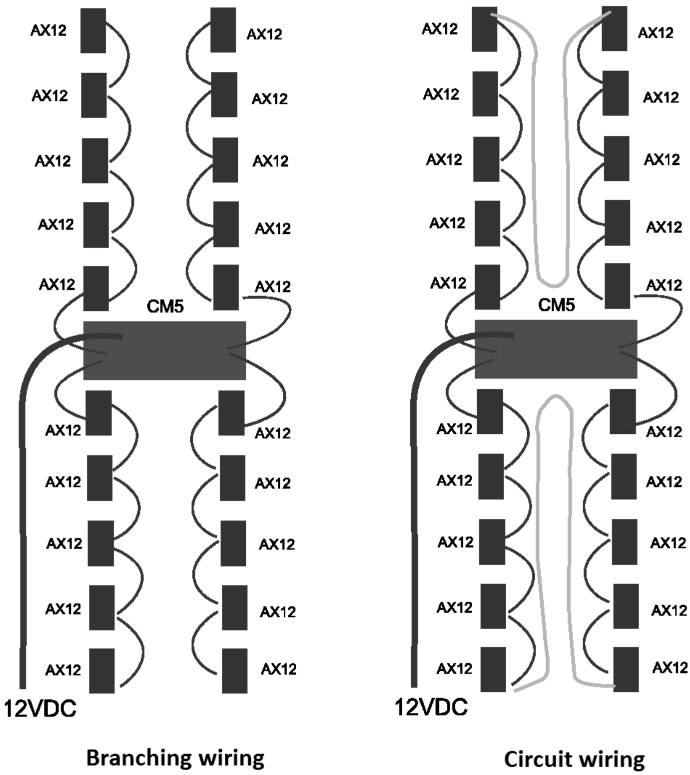


Fig. 2. Wiring diagram [source: own study]

5. ONLINE VISUALIZATION

In order to simplify programming and debugging part of development process, we have also created a CAD model of our robot using CAD Bioloid parts provided by master thesis of Pedro Teodoro from Humanoind Robot Lab, Lisboa. Robot operating system allows users to import custom 3D Solidworks models into RViz environment and pipeline them with real robot. The user is able not only visualize different robot poses and deduce particular joint positions during programming but also in reverse perform online visualization where actual joint positions are directly transferred to robot model so model and real robot position correspond in real time.

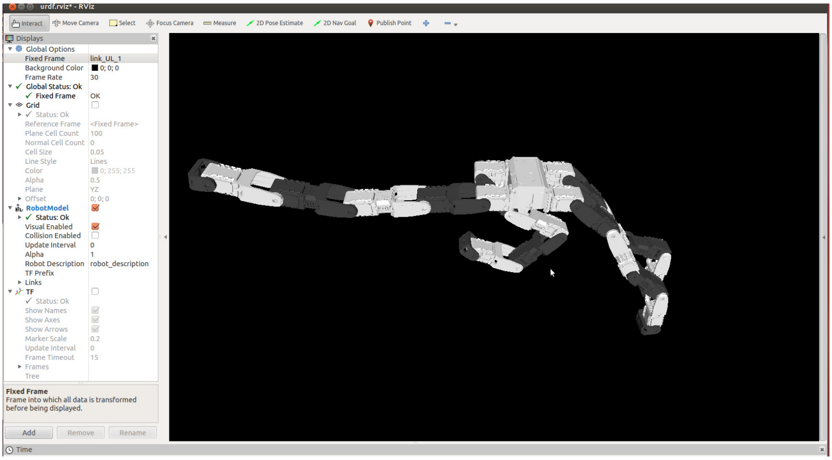


Fig. 3. Online visualization of climbing robot [source: own study]

6. LADDER CLIMBING MOTION

The whole robot movement follows basic climbing three-point rule as shown in Fig. 4, so at least three robot limbs are always in touch with ladder and only single limb performs the movement.

Up climbing sequence:

1. Starting point: Legs hanging on first step, arms hanging on second step, COG at level of first step.
2. COG movement – limbs do not change its position, but COG moves to second step level.
3. Right arm release second step and reach for third step
4. Left arm release second step and reach for third one.
5. Right leg release first step and moves to second one
6. Left leg release first step and moves to second one, while whole robot ends in "starting point".

Completing this sequence moves robot one step up in approximately 30seconds.

Down climbing is common sequence, only reversed:

1. Starting point: Legs hanging on second step, arms hanging on third step, COG at level of second step.
2. Right leg release second step and moves down to first one.
3. Left leg release second step and moves down to first one.
4. Right arm release third step and moves down to second one.
5. Left arm release third step and moves down to second one.
6. COG movement, limbs do not change its position, but COG moves down to first step level.

Down climbing is faster and takes approximately 25 seconds.

Very important detail that strongly affects success of climbing motion is procedure of grasping particular step. As stated in the beginning, step distance slightly varies therefore it is not possible to program particular motion sequences “hardly” and some robustness must be included. To overcome this difficulty we decided to use very convenient feature of dynamixel actuator called “*torque_enable*”. It is a simple ROS service that allows to switch motor torque on and off directly from code. There are three phases of every limb movement:

1. Releasing actual standpipe.
2. Movement above goal standpipe.
3. Grasping.

“*Torque_enable*” is strongly utilized in third phase, when limb hook is after previous movement located above the goal standpipe. To ensure soft and robust grasping it is necessary to release one of upper joints (shoulder or hip) of particular limb and let the gravity to finish the movement.

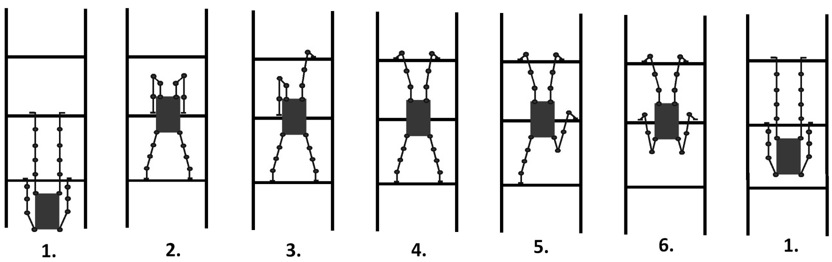


Fig. 4. Up climbing motion sequence [source: own study]

7. TESTING UNDER REAL CONDITIONS

Development and programming was realized under laboratory conditions with 6-step wooden model ladder. In this scenario, robot was able to successfully climb 5 steps up and down without any problem. To prove robot’s functionality and robustness of control algorithm we have performed several tests on real chimney standpipe ladder located near our university (Fig.5). In this case robot was able to climb several steps as well, but the movement was not that robust as under laboratory conditions due to several reasons: First of all, chimney standpipes are not strictly horizontal and its tilt varies ±15º. This construction defect causes vertical robot deflection during climbing and complicates further arm reaching movement. Another problem is related with shape of chimney standpipes, because relatively large radius of corner curvatures shorten effective grasping segment of each step. Therefore in case of slightly deflected robot it is often problem to hook the arm to following step properly, resulting in failure of climbing process.

Fig. 5. Test climbing on standpipe chimney ladder [source: own study]

8. CONCLUSIONS

The goal of this paper was to summarize results and experience gained by construction and programming of anthropomorphic ladder climbing robot. State of art overview as well as mechanical design, electronics and control algorithm were described in detail. Under laboratory conditions, robot was able to climb the ladder up and down quite robustly, but testing on real chimney has shown several issues that need to be handled in the future.. Video of climbing sequence is available at: https://www.youtube.com/watch?v=RdROmmUhG74.
First of all "sensorless" design is it not suitable for real application, so micro switches to detect pipe contact and maybe a gyroscope to keep robot balanced will be necessary. In order to speed climbing process and provide higher rigidity AX18 modules should be used since torque limitations complicated process of climbing.

Acknowledgements

This research is the result of the Project implementation: University Science Park TECHNICOM for Innovation Applications Supported by Knowledge Technology, ITMS: 26220220182, supported by the Research & Development Operational Programme funded by the ERDF."

REFERENCES

[1] BEVLY D., FARRITOR S., DUBOWSKY S.: *Action Module Planning and its Application to an Experimental Climbing Robot,* Proceedings of the 2000 IEEE International Conference on Robotics and Automation, p.4010–4015.

[2] FUJII S. et al.: *Ladder climbing control for limb mechanism robot "ASTERISK"*. Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on (p. 3052–3057). IEEE.

[3] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*. [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.
[4] HIROSE S., KAWABE K.: *Ceiling Walking of Quadruped Wall Climbing Robot NINJA-II,* Proceedings of the 1st International Conference on Climbing and Walking Robots, p.143–147, 1998.
[5] HORÁK. M, NOVOTNÝ. F, STARÝ M, ČERNOHORSKÝ J.: *New generation of mobile platform of service robot for motion along vertical wall,* Applied Mechanics and Materials, Volume 613, 2014, p. 126–131.
[6] KAJIWARA H., ARAI M., et al.: *Development of Rock-net Climbing Robot*, JSME Conference on Robotics and Mechatronics, 2004.
[7] KANZAKI T., YAMAGUCHI S.: *Current Situation and Issues Concerning the Maintenance and Management of Underground Lifeline Structures in Japan*, Proceedings of the 23rd International Symposium on Automation and Robotics in Construction, p. 293–298.
[8] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning*. Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.
[9] KUSHIHASHI Y., YOSHIKAWA K., et al.: *Development of Tree Climbing and Pruning Robot, Woody-1*, JSME Conference on Robotics and Mechatronics, 1A1-E08, 2006.
[10] MIYANAKA H., MATSUNO F. et al.: *Development of an unit type robot "KOHGA2" with stuck avoidance ability*, Proceedings of the 2007 IEEE International Conference on Robotics and Automation.
[11] NAKAI H. et al.: *Metamorphic Robot Made of Low Melting Point Alloy,* Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2002, p. 2025–2030.
[12] QUIGLEY M. et al.: *ROS: an open-source Robot Operating System*. ICRA workshop on open source software, vol. 3, no. 3.2, p. 5.
[13] SandFlea Jumping Robot by Boston Dynamics – http://www.bostondynamics.com/robot_sandflea.html
[14] ŚWIĆ A., GOLA A.: *Elements of Design of Production Systems – Methodology of Machine Tool Selection in Casing-Class FMS.* Management and Production Engineering Review, vol. 1, no. 2, 2010, p. 73–81.
[15] TADOKORO S., TAKAMORI T, OSUKA K.: *Investigation Report of the Rescue Problem at Hanshin-Awaji Earthquake in Kobe.* Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2000, p.1880–1885.

Marek Sukop[1], *Michal Špak*[2], *Mikuláš Hajduk*[3]

PROPOSAL OF FLYING ROBOT CONTROL FOR MULTI ROBOTIC SYSTEM (QUADROCOPTER)

1. INTRODUCTION

In the field of service robotics has no limits, and therefore it is possible to create a robot from almost any device [4,7]. For this it is necessary to be provided with necessary components. These components ensure that a certain degree of autonomy, which characterizes the whole of the service robots [2,6]. Just the realization of this idea to deal with our research and development, resulting in the creation of functional control system for semi-autonomous quadrocopter operated through tele operator workplace [5]. Important requirements of a control system produced by commercially produced systems do not allow the possibility of free reprogramming, ensuring eventual implementation of algorithms for performing additional functions [8].

Prior to the implementation of the control system design and selection of the components necessary to ensure stabilized flight [9]. It was important to also learn the knowledge of the principles of flight, this type of equipment, knowledge acquisition and processing of flight information and the proposal itself control algorithm, which was created in a development environment based on the Arduino programming language [1,3] Wiring. In the implementation, we have not dealt with the design, because it is based on commercially manufactured platform.

[1] Department of Robotics, Faculty of Mechanical Engineering, Technical University of Kosice, 042-00 Kosice, e-mail: marek.sukop@tuke.sk
[2] Department of Robotics, Faculty of Mechanical Engineering, Technical University of Kosice, 042-00 Kosice, e-mail: michal.spak@tuke.sk
[3] Department of Robotics, Faculty of Mechanical Engineering, Technical University of Kosice, 042-00 Kosice, e-mail: marek.sukop@tuke.sk

2. PROPOSAL OF ROBOT CONTROL

In order to ensure proper operation and reliable cooperation of all electronic parts of quadrocopter is necessary to develop appropriate control software that ensures these requirements. As Quadrocopter activity is composed of sub-activities and tasks performed by individual components can also be broken down by the control in developing the program for individual functional units (figure 1).

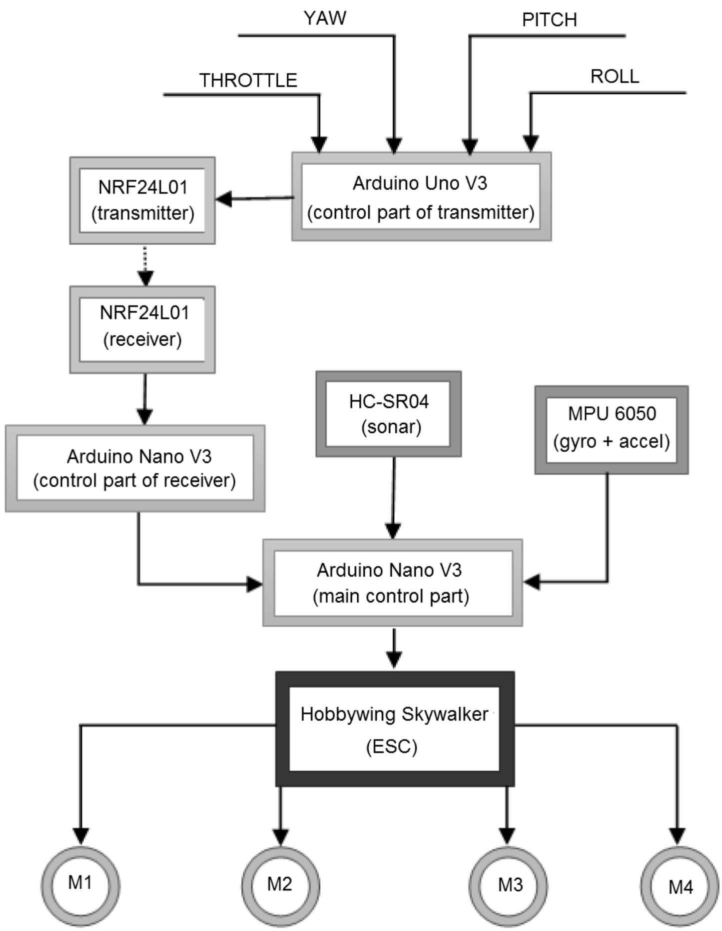


Fig. 1. Arrangement of individual members of the system control [source: own study]

3. IMPLEMENTATION OF ROBOT CONTROL

Module of remote control has the task through the input device consisting of a pair of two-way joystick potentiometers retrieve the value of the slope, angle of orientation and the amount of altitude that enters the user. Its arrangement is on Figure 2.

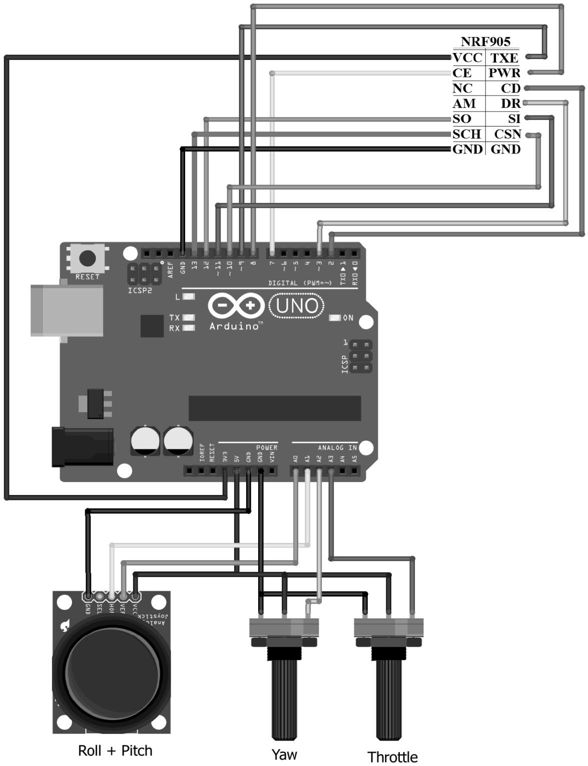


Fig. 2. Arrangement of transmitter modul
[source: own study]

In order to receive all of the following information has been designed as a receiver module, the control member is Arduino Nano. The role of the receiving module not only receive data, but they also distribute via I2C module into the flight control. After receiving the information must occur immediately process the distribution module to control the flight. This is to achieve the best response, thus reducing the time between entering the changes of motion and physical execution as low as possible. Algorithm receiving module must therefore be set up, with regard to this important requirement. Arrangement of receiver modul is on Figure 3.

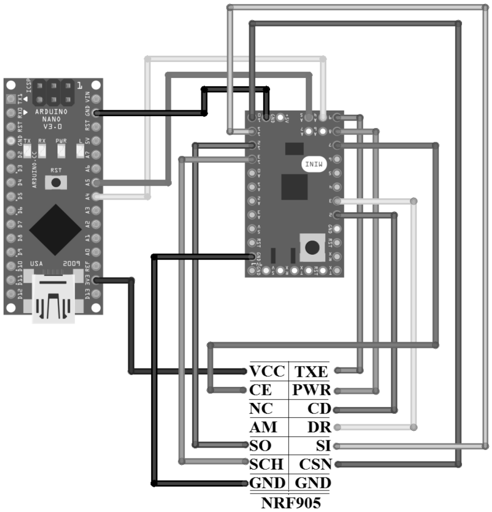


Fig. 3. Arrangement of receiver modul [source: own study]

The movement in the air provide four independent of each engine. Each one of them has the ability to influence the movement is to a large extent. As a control element was designed flight control module (Figure 4) based on the module Arduino Nano. The control module is connected inertial sensor GY521 for detecting current position Quadrocopter. Identify barriers to providing ultrasonic sensor HC-SR04.

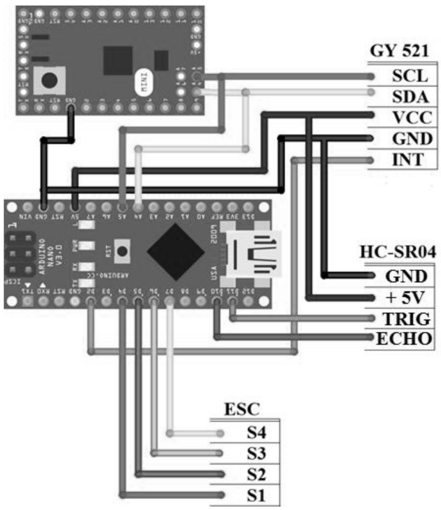


Fig. 4. Arrangement of main control modul
[source: own study]

4. CONCLUSIONS

Motion control system with hardware components based on the features of the structure Quadrocopter and BLDC motors that were planted on it, and the principle of flight amenities. In view of the specific parameters have been proposed various parts of the control system as a battery, electronic speed regulator, the necessary sensors and control element represented by the module Arduino. Specific part of implementation was the setting of PID controllers. Of experimental method was used, which does not so accurate results such as mathematical methods, but for the case of accuracy suit.

Acknowledgements

This contribution is the result of the project implementation: ITMS 26220220141 "Research modules for intelligent robotic systems".

REFERENCES

[1] ARDUINO: Language Reference [online]. Italy, 2014, [cit.2014-01-08].
[2] FEDÁK V., BAČÍK J.: *Hardware Design for State Vector Identification of a Small Helicopter Model.* Applied Mechanics and Materials, vol. 282, 2013, p. 107–115.
[3] GOLA A., SOBASZEK Ł.: *Simulation of production flow using Matlab system.* [in:] Lipski J., Świć A., *Optimization of production processes,* Wyd. Politechniki Lubelskiej, Lublin, 2013, p. 64–74.
[4] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning.* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.
[5] MIKOLAJCZYK T. et al.: *Multipurpose Mobile Robot*, Applied Mechanics and Materials, vol. 282, (2013), p. 152–157.
[6] NOVOTNÝ F., HORÁK M.: *Computer modeling of suction cup sused for Windows cleaning robot and automatic handling of glass sheets.* MM Prumyslove spektrum – MM Science Journ., 2009, p. 113–116.
[7] ŚWIĆ A., GOLA A.: *Economic Analysis of Casing Parts Production in a Flexible Manufacturing System.* Actual Problems of Economics, no. 3 (141) 2013, p. 526–533.
[8] ŠPAK M.: *Návrh riadenia servisného robota.* Diplomová práca, TU Košice, 2014, p. 88.
[9] http://arduino.cc/en/Reference/HomePage

Ján Semjon[1], *Vladimír Baláž*[2], *Marek Vagaš*[3]

PROJECT MULTIROBOTIC SYSTEMS WITH KUKA ROBOTS IN COOPERATION WITH VW SLOVAKIA

1. INTRODUCTION

Robotics with robots is located at the Department of Robotics (KR) TU Košice. Workplace was implemented in partnership with VW Slovakia. According to the standards VW SK, hardware and software and all safety features have been working so designed and constructed in Bratislava plant VW Slovakia and later revived specifically for use for educational purposes. It was subsequently moved to the premises of the laboratory, figure 1. Its dimensions reach 8.9 x 6.5 m.

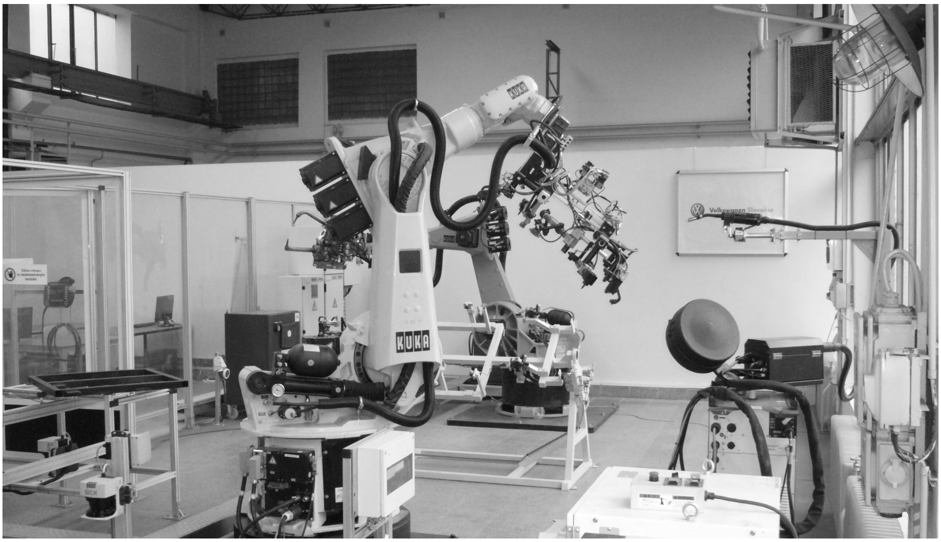


Fig. 1. Automated robotic workstation with robots [source: own study]

[1] Technická Univerzita v Košiciach, Katedra robotiky, e-mail: jan.semjon@tuke.sk
[2] Technická Univerzita v Košiciach, Katedra robotiky, e-mail: vladimir.balaz@tuke.sk
[3] Technická Univerzita v Košiciach, Katedra robotiky, e-mail: marek.vagas@tuke.sk

2. STRUCTURE OF ROBOTIC WORKSTATION

The structure of the department consists of two KUKA robots, control systems of robots, positioning unit, welder and locking control circuits to ensure safety in the workplace [5]. In figure 2 shows a plan view of and 3D model of workplace.

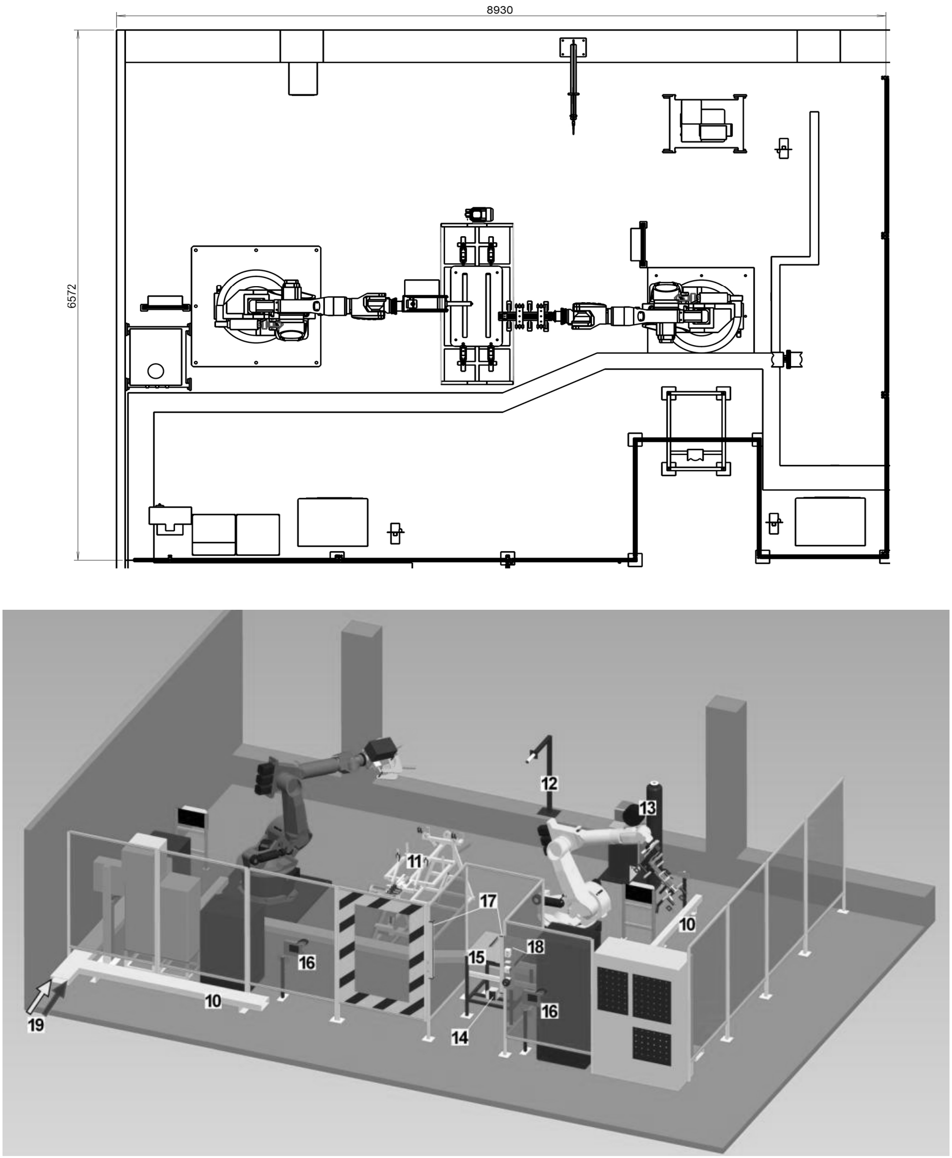


Fig. 2. The structure of the robotic workplace [source: own study]

Description robotic workstation as shown in Figure 2:

1. Robot KUKA VKR 125 designed to manipulate the object.
2. Robot KUKA VKR 125 designed for spot welding.
3. PLC – control systems work.
4. Control systems of robots.
5. Control Panels for spot welding.
6. The central switch for the whole department.
7. The cooling system of scoring pliers robot.
8. The control cabinet for power supply and air.
9. Stand 380V power supply.
10. Tray for electricity distribution and supply air.
11. Positioning unit.
12. Welding head for MIG / MAG welding.
13. The welding unit for MIG / MAG welding.
14. Scanners.
15. The loading table designed for handling object.
16 Control Panel – pendants.
17. Safety barriers.
18. Emergency stop button, illuminated sign.
19. The electrical power and compressed air to the entire department.

The first robots are equipped with scoring pliers company Nimak. The second robot is equipped with a handling head. Between robots is uniaxial positioner allowing tilting preparation into workspaces robots [9].

The equipment robotized workplace include:

- Positioning table – enable to the Institute embedded handling superstructure in two positions. The first position is for loading and unloading bodies handling robots. The second position is for spot welding performed by welding robot.
- Cooling system scoring pliers – used for cooling the electrodes scoring pliers because during spot welding process evolved and unwanted heat.
- Department for insertion and removal of welded components – perform callback consisting in the possibility of insertion and removal of parts for handling superstructure in service robotic workstation. These operations are performed using the workplace.
- Welding torch mounted on the hard shoulder – used for arc welding parts, the movements carried out by a handling robot.
- Control systems of robots and the main control system of robotic workstation – robot control systems are subject to a higher-level control system, which controls the robots in addition to all the auxiliary and safety functions of the equipment robotized workplace.

- Safety equipment, fencing – safety equipment consists of motion sensors and photocells SICK. Fencing serves as the unauthorized access to the work area of work, the gateway to the workplace is equipped with a safety mechanism which locks after opening movements of robots.

3. ALGORITHM OF WORKPLACE – CONDITIONS FOR CYCLE

The algorithm robotic workstation in figure 3 begins with an acknowledgment of the protective circuit switch on the PLC control system work. The protection circuit consists of safety barriers, laser scanners and switch on the door to enter the workplace. After confirmation, the robot A – KUKA VKR 125 with gripping effector moves from the starting position to the insertion window where using the suction cups and especially the four clamps IMI Norgren grasped object manipulation of the desk [2,3,8].

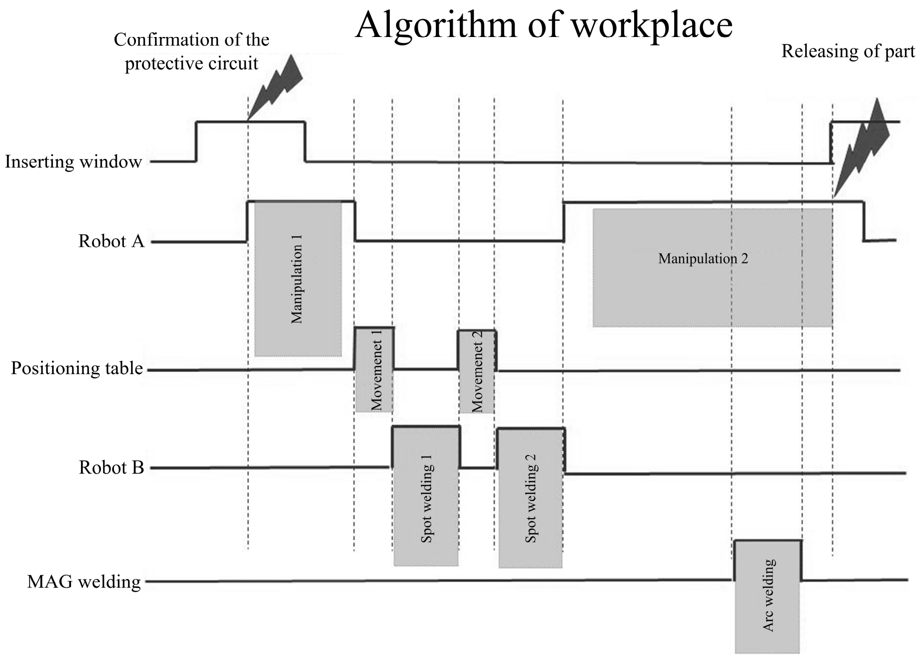


Fig. 3. Description of working procedure in the workplace [source: own study]

After a solid grasp of the subject handling the robot moves from the insertion of the window to the positioning unit. Robot slowly inserted object manipulation on the workbench positioning unit. After settling occurs to release the object grasping effectors, where the object manipulation clamped to the workbench with four clamps Tuenkers. Stepping motor positioning unit rotates the workbench with the subject of manipulation by 42 ° to position 1. This angle provide four inductive Balluff sensors that detect the movement of metal objects.

Robot B – KUKA VKR 125 technological effector designed for spot welding is moved from the starting position of the positioning unit. This robot scoring tick type X is ready for spot welding applications at the bottom of the object manipulation. After the welding which takes about 8 s leads to a transfer robot so as not to clash on the turntable, which is moved to position 2. After moving the rotary table there is a kind of scoring. which is applied to the top of the object of welding which takes about 6 s.

After the scoring, the effector of robot technology moved to its starting position and the robot grasping effector is moved to the positioning unit [1,6]. Clamps on the turntable is unhooked. Robot end effector grips object manipulation and moved with him to stand with head intended for MAG welding. The robot moves slowly with object manipulation in close proximity to the head which together carry MAG welding. After this, the welding robot with manipulation of the object moves to the insertion of the window where there is a release object manipulation on the workbench. The robot returns to the starting position and is ready for further operations [4,7].

4. CONCLUSIONS

Automated robotic workstation at the Department of Robotics is a unique example of a long-term cooperation with practice. The result is the possibility of using the workplace as the level of scientific research and teaching activities. Finally, this is an excellent prerequisite for workplace training for workers of different engineering firms.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multirobotic systems".

REFERENCES

[1] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A.: *A predictive model of multi-stage production planning*. Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[2] MIKOLAJCZYK T. et al.: *Multipurpose Mobile Robot*. Applied Mechanics and Materials, vol. 282, (2013), p. 152–157.

[3] PIOTROWSKI A., NIESZPOREK T., BORAL P.: *DP in a dispersed control system*, management and control of manufacturing process, Lublin, 2011.

[4] SjF TU Košice, KVTaR. *Manuál pre programovanie robotov KUKA*, [CD-ROM]. Košice: KVTaR, 1-99.

[5] SOBASZEK Ł, GOLA A., ŚWIĆ A.: *Creating Robust Schedules Based on Previous Production Processes,* Actual Problems of Economics, no. 8 (158) 2014, p. 488–495.
[6] ŚWIĆ A., GOLA A.: *A Method of Qualification of Parts for Production in a Flexible Manufacturing System.* Actual Problems of Economics, No. 11 (149) 2013, p. 576–585.
[7] VW Slovakia. Prezentácie. Bratislava. VW Slovakia, KR.
[8] ZUBRZYCKI J., ŚWIĆ A., TARANENKO V.: *Mathematical model of the hole drilling process and typical automated process for designing hole drilling operations.* Applied Mechanics and Materials, vol. 282 (2013), p. 221–229.
[9] http://www.kuka-robotics.com/czech_republic/cs/

Marek Vagas[1]

VARIANTS FOR THE SOLUTION OF MULTI ROBOTIC SYSTEMS

1. INTRODUCTION

A high level of automation can be found if the number of variation is small, the handling operations are not too complex and the number of assembled units is high. In case of more complex assembly problems which cause high cost automation, manual assembly can be profitable. In the last decade, advantages of multi robotic systems over the use of single robotic systems have been recognized as a key factor to achieve higher level of flexibility, efficiency and productivity of industrial robotic workplaces [2,4].

Industry has been looking at the cooperation between two industrial robots with increasing interest. As a matter of fact, multi robotic systems developed in industrial contexts have been used mainly to execute tasks not viable or even impossible for single robotic systems [3].

Coordination of two robots is much more to avoid possible collisions between them. Operators want a more precise synchronization to enable robots to work as a team and complete tasks that a single robot cannot carry out [1]. Two robots, for example, could lift an object too heavy or arched for one only, or a group of robots could work simultaneously on an object while it is moved or rotated.

These tasks require a high level of synchronization, which is now possible thanks to the new types of controllers, which allows groups of robots to perform tasks more complex than ever, see figure 1. To ensure it is taken into account these possible approaches:

1. We can consider only end-effector position from the master robot to the slave robot.
2. We can consider joint limits avoidance of slave robot to guarantee a feasible kinematic configurations.

[1] Technická Univerzita v Košiciach, Katedra robotiky, e-mail: marek.vagas@tuke.sk

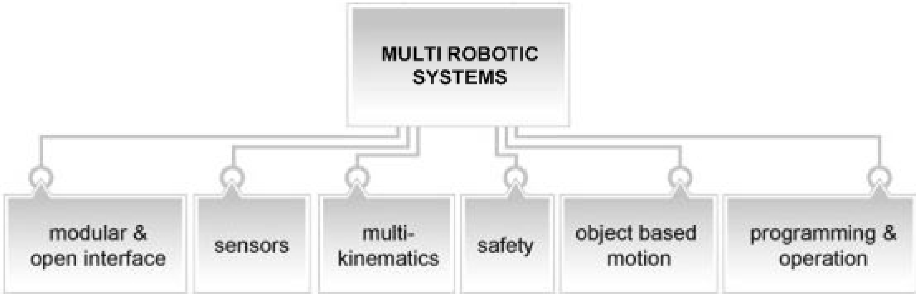


Fig. 1. Multi robotic systems [source: own study]

2. VARIANT FROM ABB

One of the variants is given by the Multimove from ABB Robotics. A MultiMove system is a system, where a common controller controls up to four robots, each equipped with its own drive module. This advanced functionality has been made possible by the processing power and modularity of the IRC5 control module that is capable of calculating the paths of up to 36 servo axes. The MultiMove functions helps to create and optimize programs for systems, where one or more robots holds the work piece and other robots operate on it [11].

When using a robot system it is important that the robots are working in the same coordinate system, see fig. 2. MultiMove exists in two different modes – Independent and Coordinated. With the MultiMove Coordinated option, a MultiMove system is able to work together on a common work piece and coordinated in a common work object. MultiMove Coordinated also includes all MultiMove Independent functionality.

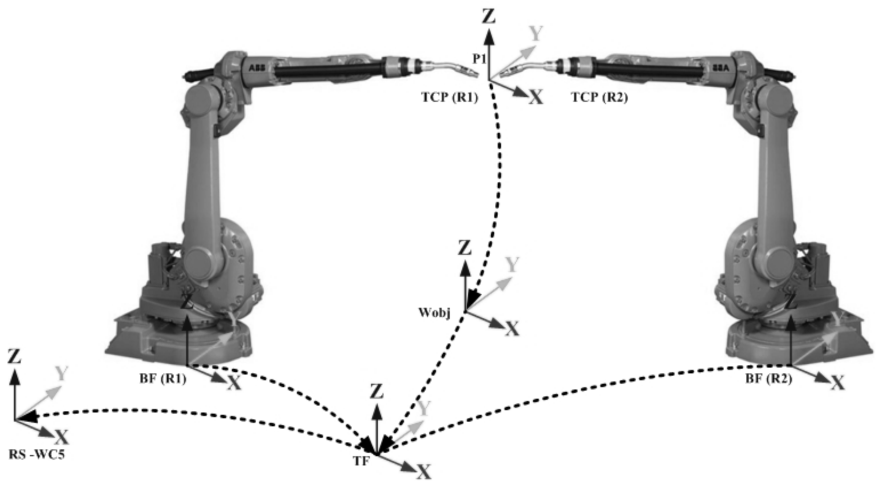


Fig. 2. ABB multirobotic system – MultiMove [source: own study]

A key to the easy implementation of MultiMove is that each robot and additional device in the cell has its own program, which may be written and edited in the ABB RAPID robot programming language. Each program may be viewed and executed totally or partly independent of each other using either the Windows style Flex Pendant graphical teach unit, which has been developed as an integral part of the IRC5 controller, or a PC. This concept of program separation in the MultiMove function is unique to ABB, see tabel 1.

Tab. 1. Instructions in MultiMove function for ABB robots [source: www.abb.com]

Instruction	Description
WaitSyncTask	WaitSyncTask is used to synchronize several task programs at a special point in the program. A WaitSyncTask instruction will wait for the other task programs. When all task programs have reached the WaitSyncTask instruction, they will continue their execution.
SyncMoveOn	SyncMoveOn is used to start synchronized movement mode. A SyncMoveOn instruction will wait for the other task programs. When all task programs have reached the SyncMoveOn, they will continue their execution in synchronized movement mode. The move instructions in the different task programs are executed simultaneously, until the instruction SyncMoveOff is executed. A stop point must be programmed before the SyncMoveOn instruction.
SyncMoveOff	SyncMoveOff is used to end synchronized movement mode. A SyncMoveOff instruction will wait for the other task programs. When all task programs have reached the SyncMoveOff, they will continue their execution in unsynchronized mode. A stop point must be programmed before the SyncMoveOff instruction.
SyncMoveUndo	SyncMoveUndo is used to turn off synchronized movements, even if not all the other task programs execute the SyncMoveUndo instruction. SyncMoveUndo is intended for UNDO handlers. When the program pointer is moved from the procedure, SyncMoveUndo is used to turn off the synchronization.
MoveExtJ	MoveExtJ (Move External Joints) moves one or several mechanical units without TCP. MoveExtJ is used to move additional axes, in a task without any robot.

3. VARIANT FROM KUKA

The RoboTeam application from KUKA Roboter is package that enables precisely coordinated teamwork between up to 15 robots through fast synchronization of the path motions. This allows the robots to work faster, and with greater precision and versatility than before. Cooperating robots allow totally new plant and cell layouts – with shorter production lines and simpler installations. In this way, load sharing makes it possible to flexibly multiply the payload capacity of standard robots [5].

At Fig. 3 is shown the controllers exchange in real time, via network connections, all data is required for synchronization and geometric coupling and any relevant safety data. If the data connection is broken or if safety – relevant data are communicated, the entire control system is switched to a safe state [12]. The controller concept is expandable. Subgroups are possible, and individual robots can belong to more than one group. Network features:

- The system is operated using a single KCP.
- Control cabinet with safety selection board for safe selection of drives.
- CR cabling separate from the rest of the network cabling.
- A fully configurable switch in the VxWorks network.
- A standard switch in the Windows network.

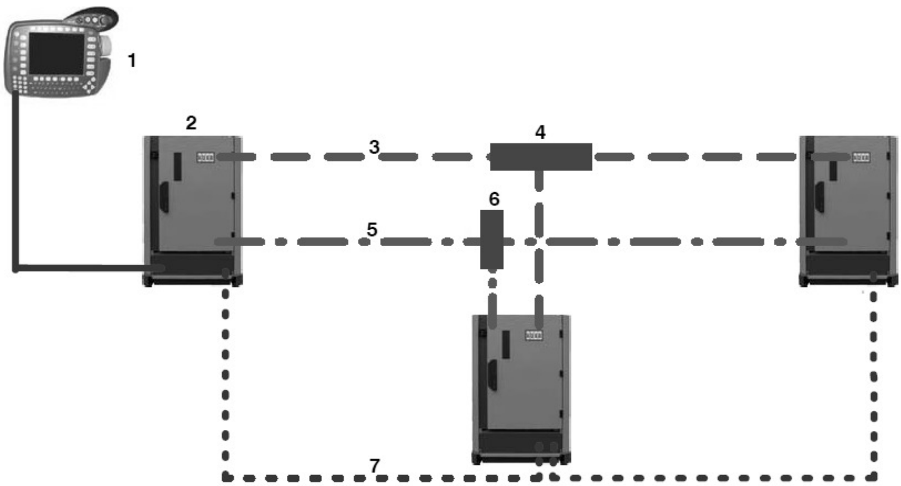


Fig. 3. Concept of KUKA controllers for RoboTeam (1 – Shared pendant KCP, 2 – KR C2 with safety selection board, 3 – Windows network, 4 – Standard switch, 5 – VxWorks network, 6 – Fully configurable switch, 7 – CR cabling) [source: own study]

Programming instructions in RoboTeam function for KUKA robots are presented in Tab. 2. These instructions are all included in KRL (robot programming language for KUKA robot) instructions for KUKA KRC2 robot controller.

Tab. 2. Instructions in RoboTeam function for KUKA robots [Source: www.kuka.com]

Instruction	Description
PROGSYNC	PROGSYNC makes it possible to start the continuous path motions of cooperating robots simultaneously. Irrespective of what motions they have been executing before, program synchronization forces a simultaneous motion start for all involved robots at synchronization point tx. The controllers then resume execution of their programs.
ENTERSPACE	ENTERSPACE permits the robot that is approaching the workspace most quickly to enter it. Slower robots are stopped.
EXITSPACE	EXITSPACE orders the robot that is in the workspace to leave it and enables the workspace. The next robot in a defined sequence is granted permission to enter.
GEOLINK	The GEOLINK command couples a robot (slave) with the base system of another robot (master). When the master is jogged, the slave follows its motions. A geometric coupling can be canceled by selecting any base reference that is not linked to the master (e.g. NULLFRAME).
SYNC	The command SYNC is used to synchronize individual motion blocks of cooperating controllers (MotionSync). Motions of several robots can be synchronized so that each robot requires the same amount of time for these motions. The command SYNC is a supplementary component that can be called and added to a LIN or CIRC motion block.
SyncCmd()	SyncCmd enables program and motion synchronization.
RemoteCmd()	RemoteCmd makes it possible to send commands to other controllers. Command execution on the local controller is interrupted for the duration of execution on the remote controller.
LK()	The LK function (“Linked Kinematic”) allows the geometric coupling of separate kinematic systems (robots). Motions of external robots are adapted to those of the local robot.

Or work pieces can be processed during transfer to the next assembly station, thereby reducing the non-productive transfer time [7]. A further advantage of the KUKA RoboTeam function is each robot keeps its standard controller. This is connected to a high-speed local network (Ethernet) via which the controllers communicate with one another and synchronize themselves. RoboTeam groups are programmed conveniently and transparently using inline forms that contain all the command parameters and exclude the possibility of incorrect entries.

Cooperating robots allow a manufacturing process that cannot be implemented with conventional production technologies: a handling robot picks up the work piece while it is still being machined in the cell, see Fig. 4. While the work piece is still being transferred, the robots from the next cell continue the machining processes in an "on-the-fly change-over". Precondition: all machines are networked in a RoboTeam.

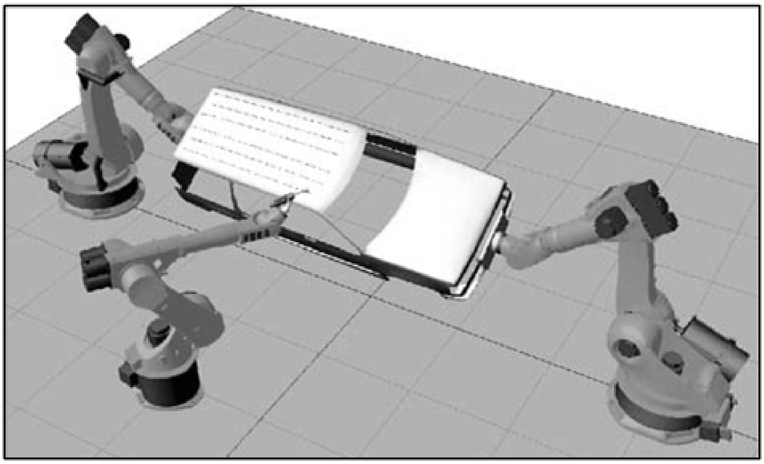


Fig. 4. KUKA RoboTeam concept [source: own study]

The advantage of this technology is that each robot retains its standard controller. This is connected to a high-speed local network (Ethernet) via which the robots communicate with one another and synchronize themselves by means of so-called geometric cooperation. One robot is in control and the others follow its lead [6]. People in this field therefore talk of it as a "master/slave technology". This also simplifies the programming, which is only slightly more demanding than for conventionally controlled industrial robots, irrespective of the size of the RoboTeam.

An additional software development on the robot controller for collision avoidance makes the interplay between the machines even simpler and safer [8].

4. COMPARISON OF MULTIROBOT FUNCTIONS

In order to make a comparison of advantages and disadvantages of the aforementioned multirobot cooperative functions, Tab. 3 is listed here to show their detailed specifications.

Tab. 3. Comparison of specification for different multirobot cooperative functions [10]

ITEM	ABB	KUKA
Function name	MultiMove	RoboTeam
Appearance time	2004	2005
Max. number of robot	4	15
Number of controller	1	n
Communication interface	Ethernet and safety signal cable	Windows and VxWorks
Instruction format	1-1	1-1

In Tab. 3, it is clear that the RoboTeam function of KUKA robot has the biggest ability to control up to 15 robots. Meanwhile, its control structure is the most complicated because n controllers are needed for RoboTeam function [10].

The MultiMove function of ABB robot has the simplest structure and only 1 controller is need in their cooperation control. Such a centralized control structure of ABB robot has limited ability and only 4 robots can be involved in 1 cooperative motion maximally.

This flexibility has a direct impact on their instruction format and numbers of controller for their cooperative function.

5. CONCLUSIONS

In this paper was described and compared two possibilities for control of multi robotic systems.

By the application of two and more cooperative robots we can reach tasks, which cannot be realized with one robot. Using only one robot for one task is more and more not effectively, nowadays.

The advantages of these workplaces are implementation of different tasks and synchronous control of each robot and their cooperation. Reasons for using more robots are also shortening cycle times, flexibility of manufacturing and quickly changed products.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11"Principles of profiling and cooperation multirobotic systems".

REFERENCES

[1] BALÁŽ V., HAJDUK. M., VAGAŠ M., SEMJON J.: *Vytváranie 3D modelov pre CAD systémy off-line programovania robotov.* Robotics and Intelligent Manufacturing Systems: zborník príspevkov z medzinárodnej konferencie: Košice, TU, 2013, p. 51–55.

[2] GOLA A., ŚWIĆ A., KRAMAR V.: *A multiple-criteria approach to machine-tool selection for focused flexibility manufacturing systems*, Management and Production Engineering Review, vol. 2, no. 4, 2011, p. 21–32.

[3] HRICKO, J., HAVLÍK, Š., HARANSKÝ, R.: *Optimization in Designing Compliant Robotic Micro-Devices [elektronický zdroj].* In: Robotics in Alpe-Adria Danube Region 19th International Workshop. Budapest: Host Obuda University, 2010, p. 397–402, IEEE Catalog Number: CFP1075JCDR.

[4] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A.: *A predictive model of multi-stage production planning*. Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[5] MIKOLAJCZYK T. et al.: *Multipurpose Mobile Robot*. Applied Mechanics and Materials, vol. 282, (2013), p. 152–157.

[6] NOVOTNÝ, F. HORÁK, M.: *Computer modeling of suction cup sused for Windows cleaning robot and automatic handling of glass sheets*. In: MM Prumyslove spektrum – MM Science Journ., 2009, p. 113–116.

[7] PIOTROWSKI A., NIESZPOREK T., BORAL P.: *DP in a dispersed control system, management and control of manufacturing process*, Lublin, 2011.

[8] ŚWIĆ A., WOŁOS D., ZUBRZYCKI J, OPIELAK M., GOLA A., TARANENKO V.: *Accuracy Control in the Machining of Low Rigidity Shafts*. Applied Mechanics and Materials, vol. 613, 2014, p. 357–367.

[9] YAHUI GAN, XIANZHONG DAI, DONGWEI LI: *Off-Line Programming Techniques for Multirobot Cooperation System*. International Journal of Advanced Robotic Systems, 2013, Vol. 10, p. 282.

[10] YAHUI GAN, XIANZHONG DAI, DONGWEI LI: Off-Line Programming Techniques for Multirobot Cooperation System.

[11] http://www.abb.com/product

[12] http://www.kuka/robotics.com/en/products/software

Juraj Beniak [1], *Peter Križan, Miloš Matúš*

LAYERING PRECISION FOR SMALL FUSED DEPOSITION MODELING DEVICES

1. INTRODUCTION

In the field of Rapid Prototyping, there is many of devices, which are used for prototypes preparation, but also the machines which could be used for production and could be also named as Rapid Manufacturing machines. FDM or Fused Deposition Modeling Machines are producing the models from plastic material. Basic principle is, that the plastic material is extruded and deposited through heated nozzle. As an deposited material could be used ABS, Polycarbonate (PC), PC-ABS or in these latter days also PLA (Polylactic acid), what if ecologically friendly and for use really easy plastic material.

This paper will introduce the real situation with model layering. The layering if closely connected with model accuracy.

2. FUSED DEPOSITION MODELING

This technique use one or two materials. The low cost FDM 3D printers use just one material, with one heating nozzle. The professional printers use 2 materials. One of them is modeling model material, used to build model. Second, support material used for build support structure on areas where modeling material will overhang the rest of model [1]. This technique works on similar principle as fuse-gun [2]. The model material is mostly ABS or PLA material, but we can see also the special materials like for example LayWood, what is mixture of 40% recycled wood with polymer as a binder. The material is unspool from spool to fuse-head, where is melted and deposited on working table. Support material is after completing of model break away or dissolved in special bath [4].

FDM is probably the most widespread Rapid Prototyping system which could be seen in the practice. The reason is probably that the patents regarding the basic of this technology is already expired. Also this technology use really easy available materials, which could be bought all over the word for low price.

[1] Slovak University of Technolgy in Bratislava, Faculty of Mechanical Engineering, Slovak Republic, e-mail: juraj.beniak@stuba.sk

The technological principle of FDM is easy to design, manufacture and control. As mentioned above, we can use basically two types of model material, which are ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid). Less then this we can see also materials as LayWoood what is the new extrusion material allows to print objects that look and smell like wood when finished. LayWood as a filament is made from 40% recycled wood that is combined with polymer binders allowing it to be melted and extruded like all of the other commercially available 3D filaments on the market today [3].

The ABS filament as a constructional material is widely used in the industry, for example as an interior parts material. So it can be easy printed also parts for real use. It depends just what material properties or part surface is requires.

The PLA filament is a new, biodegradable material, which is environmental friendly. Also the advantage of this material is, that their use for 3D printers is more easy then ABS. Require lower heating temperature of nozzle, the parts are not so predisposed for deformation and do not require table heating.

3. THEORETICAL AND REAL LAYER THICKNESS

The producers and distributors of FDM machines present than the new layer is created only if you cross the number which present the layer thickness. For example we set on the machine the layer thickness to 0,25 mm, for the model thickness 3 mm there should be 12 layers and the number of layers will increase to 13 only if we overcome the value 3,25 mm.

But the real situation is little bit different (Tab. 1). On the table 1 we can see the minimum and the maximum theoretical thickness, when the software for model layering increase the number of layers. We can see that there is interval 0,249mm for each layer. There is enough to increase the thickness value just by 0,001mm and the software will add new layer. This means that if we add to 3D CAD model just 0,001 mm, the real thickness of created model will increase by 0,25 mm, which affect the accuracy of final plastic model build on FDM device.

Tab. 1. The minimum and maximum theoretical thickness for layer changing

Layer No.	**12**		**13**		**14**		**15**	
Thickness (mm)	2,875	3,124	3,125	3,374	3,375	3,624	3,625	3,874

When we then measured the real thickness on created models with known number of layers, we could state by statistical methods the average thickness values. This average values are shown on Table 2. It does not matter if the CAD model have thickness 2,875 mm or 3,124 mm, the final model have the same number of layers 12. When we place the measured values from table 1 and table 2, to the one figure, we can see, where from the interval of each layer is the real thickness of model with presented number of layers.

Tab. 2. Measured values of model thickness for each layer

Layer No.	12	13	14	15	16	17	18	19
Thickness (mm)	3,039	3,286	3,547	3,790	4,028	4,230	4,481	4,766

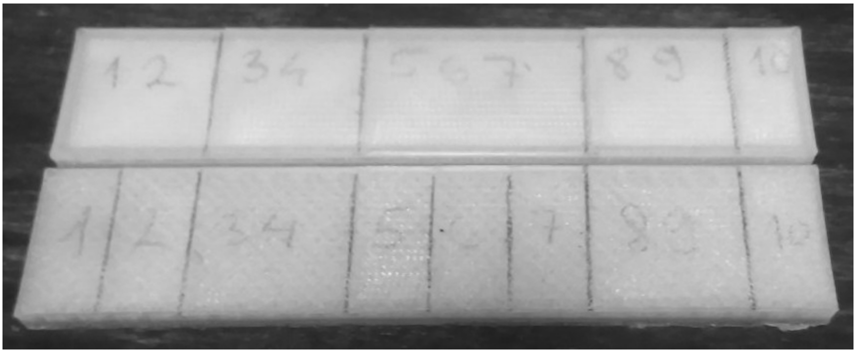


Fig. 1. Two models of stairs graded on 0,1mm. The top model is produced with layer thickness 0,25 mm. The bottom model is created with 0,125 mm layer thickness [source: own study]

On the Fig. 1 we can see the models created with different layering. On the top is the model created with layer thickness 0,25 mm. On the bottom is model with layer thickness 0,125 mm. There should be 10 stairs on each model, how it is designed in CAD system. But because of mentioned method of creating of layers, we can see that the top model is divided just to 5 parts (stairs) and the bottom model is divided to 8 stairs, which is much better regarding to required final design.

The same as the tables mentioned above (Tab. 1 and Tab. 2) which are prepared and measured for 0,25 mm layering, are prepared also for 0,125 mm layering.

On the Figure 2 we can really easy estimate the final accuracy of created model. The maximum inaccuracy can be just half of layer thickness, so in our case if could be 0,125 mm. But as we stated before, the small thickness change 0,001mm, can make the inaccuracy about 0,25 mm, which is really significant if we want to us created model for real use or the part which should to fit to other prepared assembly.

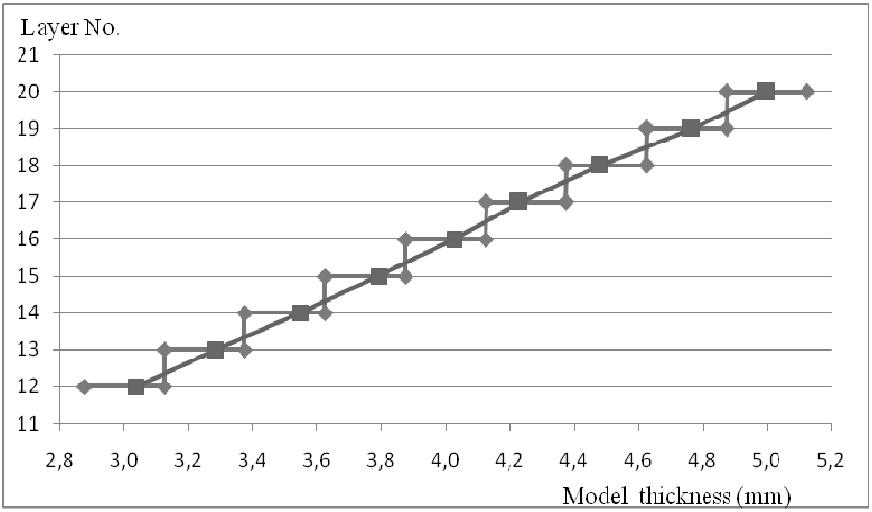


Fig. 2. Comparison of layer increasing depended from model thickness. Blue broken line present the layer change; Red sloping line present the measured values for each layer [source: own study]

4. CONCLUSIONS

Many producers of FDM devices present, that the new layer is created by software, when the thickness reach the number which present the layer thickness. But the real situation is much different. We had to make theoretical examination, with what thickness the number of layers are changing, and what if the real thickness of final model. It could easy happen, that the theoretical and real thickness are much different. That is why we have to know the basic behavior of FDM system, which should be used for model creation.

REFERENCES

[1] CHUA C. K., LEONG K. F., LIM C. S.: *Rapid Prototyping, Principles and Applications*. Nanyang Technological University, Singapore, World Scientific Co. Pte. Ltd, 2003.

[2] DUC PHAM, OBE FRENG, STEFAN DIMOV: *Rapid Prototyping, a time compression tool, manufacturing engineering centre*. Cardiff University.

[3] WALTERS R.: *Laywood filament lets you 3D print with wood*, Available in: http://www.geek.com

[4] BENIAK, J.: *Systémy Rapid Prototyping*. Bratislava: Nakladateľstvo STU, 2014, p. 133.

Lucia Koukolová[1]

RESEARCH ISSUES IN THE AREA OF MULTI ROBOTIC SYSTEMS

1. INTRODUCTION

The study of multi-robot systems has grown significantly in recent years [1]. This is not surprising as continually improving technology has made the deployment of multi-robot systems consisting of increasingly larger numbers of robots possible [14]. Task domains well-suited to multi-robot solutions are expanding. With the growing interest in multi-robot systems comes the expectation that, at least in some important respects, multiple robots will be superior to a single robot in achieving a given task. Potential advantages of multi-robot systems over a single robot system are frequently discussed in the literature. For example, total system cost, it is frequently claimed, may be reduced in many domains by utilizing multiple simple and cheap robots as opposed to a single complex and expensive robot. The inherent complexity of some task environments may require the use of multiple robots as the necessary capabilities are too substantial to be met by a single robot. Furthermore, multiple robots are often claimed to increase system efficiency, robustness, and flexibility by taking advantage of inherent parallelism and redundancy.

Several new robotics application areas, such as underwater and space exploration, hazardous environments, service robotics in both public and private domains, the entertainment field, and so forth, can benefit from the use of multi-robot systems. In these challenging application domains, multi-robot systems can often deal with tasks that are difficult, if not impossible, to be accomplished by an individual robot [8]. A team of robots may provide redundancy and contribute cooperatively to solve the assigned task, or they may perform the assigned task in a more reliable, faster, or cheaper way beyond what is possible with single robots.

The field of cooperative autonomous mobile robotics is still new enough that no topic area within this domain can be considered mature. Some areas have been explored more extensively, however, and the community is beginning to understand how to develop and control certain aspects of multi-robot teams.

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotics, B. Nemcovej 32, Kosice, Slovakia, e-mail: lucia.koukolova@tuke.sk

In this paper there is presented the review of identified key open research issues with each topic area. The six principle topic areas of multi-robot systems that we have identified are:

- Communication,
- Architectures, task allocation, and control,
- Localization, mapping, and exploration,
- Manipulation and Motion coordination,
- Reconfigurable robots.

2. COMMUNICATION

The issue of communication in multi-robot teams has been extensively studied since the inception of distributed robotics research. Distinctions between implicit and explicit communication are usually made, in which implicit communication occurs as a side-effect of other actions, or "through the world", whereas explicit communication is a specific act designed solely to convey information to other robots on the team. Several researchers have studied the effect of communication on the performance of multi-robot teams in a variety of tasks, and have concluded that communication provides certain benefit for particular types of tasks. Additionally, these researchers have found that, in many cases, communication of even a small amount of information can lead to great benefit.

More recent work in multi-robot communication has focused on represent-tations of languages and the grounding of these representations in the physicalworld [7]. Additionally, work has extended to achieving fault tolerance in multi-robot communication, such as setting up and maintaining distributed communications networks and ensuring reliability in multi-robot communications [10].

3. ARCHITECTURES, TASK ALLOCATION, AND CONTROL

A great deal of research in distributed robotics has focused on the development of architectures, task planning capabilities, and control. This research area addresses the issues of action selection, delegation of authority and control, the communication structure, heterogeneity versus homogeneity of robots, achieving coherence amidst local actions, resolution of conflicts, and other related issues. Each architecture that has been developed for multi-robot teams tends to focus on providing a specific type of capability to the distributed robot team. Capabilities that have been of particular emphasis include task planning, fault tolerance, swarm control, human design of mission plans, role assignment [3,11], and so forth.

4. MANIPULATION AND MOTION COORDINATION

Enabling multiple robots to cooperatively carry, push, or manipulate common objects has been a long-standing, yet difficult, goal of multi-robot systems. Many research projects have dealt with this topic area; fewer of these projects have been demonstrated on physical robot systems. This research area has a number of practical applications that make it of particular interest for study. Numerous variations on this task area have been studied, including constrained and unconstrained motions, two-robot teams versus swarm-type teams, compliant versus noncompliant grasping mechanisms, cluttered versus uncluttered environments, global system models versus distributed models, and so forth. Perhaps the most demonstrated task involving cooperative transport is the pushing of objects by multirobot teams. This task seems inherently easier than the carry task, in which multiple robots must grip common objects and navigate to a destination in a coordinated fashion. A novel form of multi-robot transportation that has been demonstrated is the use of ropes wrapped around objects to move them along desired trajectories [5].

Another popular topic of study in multi-robot teams is that of motion coordination. Research themes in this domain that have been particularly well studied include multi-robot path planning, traffic control, formation generation, and formation keeping. Most of these issues are now fairly well understood, although demonstration of these techniques in physical multi-robot teams (rather than in simulation) has been limited. More recent issues studied within the motion coordination context are target tracking [12], target search, and multi-robot docking [5] behaviors.

5. RECONFIGURABLE ROBOTS

Even though some of the earliest research in distributed robotics focused on concepts for reconfigurable distributed systems, relatively little work has proceeded in this area until the last few years. More recent work has resulted in a number of actual physical robot systems that are able to reconfigure. The motivation of this work is to achieve function from shape, allowing individual modules, or robots, to connect and re-connect in various ways to generate a desired shape to serve a needed function. These systems have the theoretical capability of showing great robustness, versatility, and even self-repair.

Most of the work in this area involves identical modules with interconnection mechanisms that allow either manual or automatic reconfiguration. These systems have been demonstrated to form into various navigation configurations, including a rolling track motion, an earthworm or snake motion [4], and a spider or hexapod motion [4]. Some systems employ a cube-type arrangement, with modules able to connect in various ways to form matrices or lattices for specific functions [2,15].

6. CONCLUSIONS

It is clear that since the inception of the field of distributed autonomous mobile robotics less than two decades ago, significant progress has been made on a number of important issues. The field has a good understanding of the biological parallels that can be drawn, the use of communication in multirobot teams, and the design of architectures for multi-robot control. Considerable progress has been made in multi-robot localization/mapping/exploration, cooperative object transport, and motion coordination. Recent progress is beginning to advance the areas of reconfigurable robotics and multi-robot learning.

Acknowledgements

This paper is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multi-robotic systems".

REFERENCES

[1] ARAI T., PAGELLO E., PARKER L. E.: *Advances in Multi-Robot Systems.* IEEE Transactions on Robotics and Automation, vol. 18, no. 5, 2002.

[2] BOJINOV H., CASAL A., HOGG T.: *Emergent structures in moduluar selfreconfigurable robots,* In: Proceedings of the IEEE International Conference on Robotics and Automation, p. 1734–1741, 2000.

[3] CANDEA C. et al.: *Coordinating in multi-agent robocup teams*. Robotics and Autonomous Systems, 36 (2–3), 2001, p. 6786.

[4] CASTANO A., CHOKKALINGAM R., WILL P.: *Autonomous and selfsufficient CONRO modules for reconfigurable robots.* Proceedings of the Fifth International Symposium on Distributed Autonomous Robotic Systems (DARS 2000), 2000, p. 155–164.

[5] DONALD B., GARIEPY L., RUS D.: *Distributed manipulation of multiple objects using ropes*. Proceedings of IEEE International Conference on Robotics and Automation, 2000, p. 450–457.

[6] JONES C., SHELL D., MATARIC M. J., GERKEY B.: *Principled Approaches to the Design of Multi-Robot System.*

[7] JUNG D., ZELINSKY A.: *Grounded symbolic communication between heterogeneous cooperating robots*, In: Autonomous Robots, 8(3), 2000, p. 269–292.

[8] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A.: *A predictive model of multi-stage production planning.* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[9] MINTEN B., MURPHY R., HYAMS J., MICIRE M.: *A communication-free behavior for docking mobile robots.* Proceedings of Fifth International Symposium on Distributed Autonomous Robotic Systems (DARS 2000), 2000, p. 357–367.

[10] MOLNAR P., STARKE J.: *Communication fault tolerance in distributed robotic systems.* Proceedings of Fifth International Symposium on Distributed Autonomous Robotic Systems (DARS 2000), p. 99–108.

[11] PAGELLO E. et al.: *Emergent behaviors of a robot team performing cooperative task.,* Advanced Robotics, 2002.

[12] PARKER L. E., TOUZET C.: *Multi-robot learning in a cooperative observation task.* Distributed Autonomous Robotic Systems 4, Springer, 2000, pp. 391-401.
[13] PARKER L. E.: *Current Research in Multi-Robot System.* Journal of Artificial Life and Robotics 7.
[14] ŚWIĆ A., WOŁOS D., ZUBRZYCKI J., OPIELAK M., GOLA A., TARANENKO V.: *Accuracy Control in the Machining of Low Rigidity Shafts,* Applied Mechanics and Materials, Vol. 613, 2014, pp. 357–367.
[15] UNSAL C., KHOSLA P. K.: *Mechatronic design of a modular selfreconfiguring robotic system,* In: Proceedings of the IEEE International Conference on Robotics and Automation, p. 1742–1747, 2000.

Arkadiusz Gola[1], Łukasz Sobaszek[2], Antoni Świć[2]

SELECTED PROBLEMS OF MODERN MANUFACTURING SYSTEMS DESIGN AND OPERATION

1. INTRODUCTION

The 20th century was a period of continuous challenges that both production companies and designers of manufacturing systems had to stand up to these. It was a result of technical and technological progress unknown in history so far, process of globalization moving forward in frantic pace, increasing level of competition, and also changeable and more and more superior requirements of customers. The same, both methods of production and organization of manufacturing systems were a subject of constant evolution [2,9,10].

Manufacturers today face more challenges than ever before due to the highly volatile market, which creates large fluctuations in product demand. To remain competitive, companies must design manufacturing systems that not only produce high-quality products at low cost, but also face to market changes in an economical way [25]. The cost of building a new manufacturing system may be between 50 million dollars to over 2 billion (a microprocessor fabrication facility), and its average lifetime is 12–15 years [13]. Therefore making investment decision in new manufacturing systems requires knowledge in engineering as well as in finance and economics. Particularly, manufacturing system's planning includes a sequence of important decisions as follows:

1. Decide whether to invest at all in a new production system, and, if to invest, in which type of system.
2. Based on product sale forecasting and estimated capital investment, determine whether to invest in dedicated, flexible, or portfolio capacity.
3. Calculate the cycle time of each operation and the total time needed for the whole process to produce one product.
4. Optimize the system configuration such that a proper line balancing maximizes system throughput, and tooling cost is minimized to reduce capital investment.

---

[1] Lublin University of Technology, Department of Enterprise Organization, Nadbystrzycka Str. 38, 20-618, Lublin, Poland
[2] Lublin University of Technology, Institute of Technological Systems of Information, Nadbystrzycka Str. 36, 20-618, Lublin, Poland

5. Find out the buffer capacity that optimizes the system throughput.
6. Determine the projected operations costs; it is more challenging when flexible systems that produce several products are employed.
7. Consider system responsiveness to changing orders of customers; responsiveness impacts the system throughput.
8. Calculate the optimal speed of each machine; it will impact the whole system throughput.

Designing a system is not a sequential process that follows the above mentioned steps but is an iterative process that iterates among the above listed points until converging gradually to the optimal economic solution. For example, the system configuration affects the tooling cost, which, in turn, has an effect on the capital cost, but the latter is needed to determine the system type. Moreover the system operations cost impacts profit, and may change decisions about the total installed capacity.

In this article we focus on several aspects that have to be taken into account in the process of modern manufacturing systems design. In particular, the problems of manufacturing system selection as a function of products life-cycle, capacity planning, system configuration and their impact for the financial and operational effectiveness of the system are presented. Moreover the problem of robust scheduling was shortly described.

2. MODERN CONCEPTIONS IN MANUFACTURING SYSTEMS DESIGN

It is well known that Henry Ford's invention of the moving assembly line in 1913 marked the beginning of the mass production paradigm. Yet it is less known that mass production was made possible only through the invention of dedicated machining lines that produced the engines, transmissions and main components of automobiles. Such dedicated manufacturing lines have a very high rate of production for the single part type they produce, and they are very profitable when demand for this part is high. These dedicated transfer lines were the most profitable systems for producing large quantities of products until the mid-1990s [15].

The invention of NC and later CNC in the 1970s, facilitated creation of flexible manufacturing systems (FMS) in the early 1980s [6,7]. Stecke and Solberg were the first to formalize a mathematical solution for flexible manufacturing systems [20]; already in 1981 they described the operation policies of FMS for a job shop consisting of nine machines interconnected by an automatic material handling mechanism [21]. Due to the high initial investment cost, however, close to twenty years elapsed before flexible manufacturing systems were able to penetrate the transportation powertrain industry, which is the largest market for FMS [15]. At that time, in the 1980s and 1990s the strategic goals of manufacturing enterprises were productivity, quality and flexibility [19].

In the mid-1990s, enhanced globalization and worldwide competition made it clear that FMS provide only a partial economic solution in a competitive market. The typical FMS serial structure used in industry (though not in job shops) facilitated changes in products manufactured, but it yielded a relatively slow production rate and did not provide the volume flexibility for responding to the unexpected changes in demand resulting from global completion. Cohran [4] noted that manufacturing system designs must be capable of stysfying a company objectives. When demand fluctuates, the strategic objective is to meet demand. This can only be accomplished by up-scaling the system's physical structure. But cost effective scalability through modifications in the system's physical cannot be accomplished with traditional FMS. Therefore, in the late 1990s two modern types of manufacturing systems (reconfigurable manufacturing systems and focused flexibility manufacturing systems) have been proposed.

2.1. Reconfigurable Manufacturing System (RMS)

Idea of RMSs was invented in 1999 in the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS) at the University of Michigan College of Engineering [14].The RMS main goal is summarized by the statement – *Exactly the capacity and functionality needed, exactly when needed.*

A reconfigurable manufacturing system (RMS) having an adjustable structure is designed based upon market demand and can be readily changed from a first desired production capacity to a second desired production capacity to manufacture a desired amount of product from a family of products [24]. RMSs are marked by six core reconfigurable characteristics, as summarized in Tab. 2.

As distinguished from flexible manufacturing systems (FMSs), an RMS has the structure which allows for rapid adjustment of production capacity and functionality, in response to new market circumstances, by basic change of its hardware and software components. So, while the structure of DMLs and FMSs are static, RMSs are dynamic with level of flexibility, capacity and functionality directly fitting the needs of the system in any moment of its life (Fig. 1).

RMSs can be noticed as an answer to the need for facing continuous changes in the production problems. In fact, reconfigurability describes the operating ability of a production system or device to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements.

Tab. 1. Characteristics and principles of RMS [15]

Reconfigurable characteristics	Description
Customization (flexibility limited to part family)	System or machine flexibility limited to a single product family, thereby obtaining customized flexibility.
Convertibility (design for functionality changes)	The ability to easily transform the functionality of existing systems and machines to suit new production requirements.
Scalability (design for capacity changes)	The ability to easily modify production capacity by adding or subtracting manufacturing resources (e.g. machines) and/or changing components of the system.
Modularity (components are modular)	The compartmentalization of operational functions into units that can be manipulated between alternate production schemes for optimal arrangement.
Integrability (interfaces for rapid integration)	The ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that facilitate integration and communication.
Diagnosability (design for easy diagnostic)	The ability to automatically read the current state of a system to detect and diagnose the root causes of output product defects, and quickly correct operational defects.

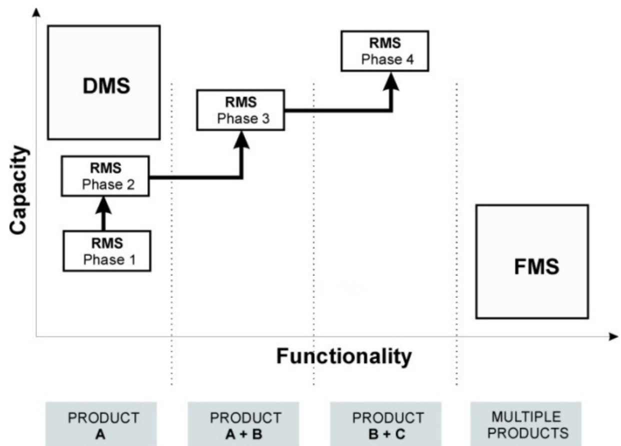


Fig. 1. Capacity and functionality of different forms of manufacturing systems [15]

2.2. Focused Flexibility Manufacturing System (FFMS)

The second modern conception of manufacturing systems design is a conception of Focused Flexibility Manufacturing Systems (FFMSs). FFMSs represent also a competitive answer to cope with the need of customized flexibility and they guarantee the optimal trade-off between productivity and flexibility [23]. Moreover, the customization of flexibility on specific production problems leads to the minimization of the system cost during its life-cycle. Indeed, the flexibility degree in FFMSs is related to their ability to cope with volume, mix and technological changes, and it must take into account both present and future changes [24].

The required level of system flexibility impacts in the architecture of the system and the explicit design of flexibility often leads to hybrid systems, i.e. automated integrated systems in which parts can be processed by both general purpose and dedicated machines. This is a key issue of FFMSs and results from the matching of flexibility and productivity that characterize FMSs and DMSs, respectively.

FFMSs are hybrid systems, in the sense that they can be composed both of general purpose and dedicated resources. This innovative architecture derives from the consideration that system flexibility is related both to the flexibility of each single selected resource and to the interaction among the resources which compose the system. For instance, a flexible system can be composed of dedicated machines and highly flexible carries.

At first sight FFMSs could appear to be similar to Reconfigurable Manufacturing Systems (RMSs); the difference between these two classes of systems is in the timing of flexibility acquisition. Deciding about flexibility and reconfigurability means to consider two options. The first option deals with designing a dedicated system in which the reconfiguration option can be implemented in the future when production changes occur. This leads to design a system with the minimum level of flexibility required to cope with the present production problem. In this case FFMSs and RMSs have similar performance. The alternative option is to purchase more flexibility than the amount strictly required by the present production problem in order to avoid future system reconfigurations and ramp-ups. In this case, FFMSs have some “extra” flexibility designed to cope with future production changes, i.e. degree of flexibility designed to cope with future production changes, i.e. a degree of flexibility tuned both on present and future production problems.

3. THE PROBLEM OF MANUFACTURING CAPACITY PLANNING

Beside the task of selection the type of manufacturing system, the optimal investment in the system capacity is a major decision to make. As defined in [1], flexible capacities "possess the ability to change over to produce a set of products very economically and quickly". Therefore, flexible systems may alleviate unfavorable effects of demand uncertainties. However, the versatility to produce multiple products often requires higher investment costs compared to dedicated systems that can only produce one type of products.

The problem of capacity planning must be sold in two stages. First, assuming that strategic investment decision is already given, we compute the maximum possible operating revenue during the entire lifetime of all products (i.e., the planning horizon). Next, we make the strategic capacity decision by choosing the recommended installed capacities that will generate the maximum profit that is corresponding to the highest operating revenue minus investment costs.

The problem may be formulated as a linear program with an optimization cost index [13]. Cost index $\Psi(d,k)$ expresses the revenue that can be achieved for a given capacity investment decision *k*, and for any fulfillment of product demands *d* over the planning horizon.

$$\Psi(d,k) = \max_{x,y} \sum_{t=1}^{T} \beta^{t-1}[p_A(x_A^t + y_A^t) + p_B(x_B^t + y_B^t)] \tag{1}$$

subject to constraints:

$$x_A^t \le k_A \qquad \forall t = 1,\dots,T \tag{2}$$

$$x_B^t \le k_B \qquad \forall t = 1,\dots,T \tag{3}$$

$$y_A^t + y_B^t \le k_{AB} \qquad \forall t = 1,\dots,T \tag{4}$$

$$x_A^t + y_A^t \le d_A^t \qquad \forall t = 1,\dots,T \tag{5}$$

$$x_B^t + y_B^t \le d_B^t \qquad \forall t = 1,\dots,T \tag{6}$$

The decision variables x_A^t and x_B^t denote, respectively, how many units of dedicated capacity A and B are needed to fill period *t* demand, whereas the decision variables y_A^t and y_B^t denote the optimal allocation of the flexible capacity between products. In addition, β is the discount factor per period that is used to calculate the NPV of the revenues, $\beta = 1/(1+r)$, where *r* is the annual rate of return.

Constraints (2)–(6) guarantee that one will assign neither more capacity than the maximum available, nor more capacity than demand (i.e., the production quantities within a period do not exceed available capacity and are bound by the demand).

Having obtained the maximum operating revenue, it is possible now to write the strategic decision problem of determining the optimal capacity investments *k*.

$$\max_{k} \quad E_d(R(d,k)) - c * k' \tag{7}$$

In above formulation, $E_d[R(d,k)]$ is expected value of the operative revenue where the expectation is taken over demand distributions and c*k' represents the total investment costs. The firm's objective is to maximize E_d. Numerical example exploited above presented model for the firm producing two products over a planning horizon during which product demands possess uncertainties was presented in [3].

4. PROBLEM OF MANUFACTURING SYSTEM CONFIGURATION

The next aspect of economical manufacturing system design is to calculate the individual operation times that are needed to produce the part, where the total production time *t* is given [13]. Producing a part may be, for example, machining a part by a system composed of machining centers and lathes, or assembling a part by automation or by workers. Machining a part requires the calculation of the machine optimal cutting speeds which will affects the total machining time per part, machines reliability [16], and will eventually affect the number of machines needed in the system. If the system capacity (which is based on forecast demand) and the total time needed to produce part are given, it is possible to calculate the minimum number of machines or stations needed in the system.

If the daily demand is *D* (parts/day), and the total production time per part is *t* (minute/part), the minimum number of machines *M,* needed in the system is calculated by the equation:

$$M = \frac{Q * t}{A * R} \tag{8}$$

where: A – machine availability (minutes a day),
R – machine reliability.

When the number of machines is calculated, the next step is to decide upon the right configuration of a system that is composed of M machines. There may be several ways to configure a multi-stage manufacturing system with a given number of machines. Figure 2 shows three example configurations, each with twelve machines and each produces two parts A and B. There are configurations that require a large investment in tooling (Fig. 2c); in others a complex material handling system increases cost. Note that in the configuration in Fig. 2a, each machine performs about one sixth of the operations needed to complete the part, and therefore the total number of tools in this system is smaller than in the other two configurations.

There are also cooperation considerations in selecting a configuration. If demand for part A increases by 25% and the same day the demand for Part B decreases by 25%, the configuration in Fig. 2c can supply the new demand (nine machines produce A and three B). Satisfying the new demand with the other two systems will not be that simple and will require tool changes during the day, which will reduce the daily throughput. Therefore, the configuration in Fig. 2c has the best operational responsiveness of these three systems. This system, however requires more tools and machines with larger tool magazines, and therefore its capital investment cost is higher.

Let us compare the number of cutting tools needed to place in the tool magazines of each system configuration presented in Fig. 2. Assume that 20 different cutting tools are needed to produce part A, and additional 30 tools are needed for part B. In configuration (a) the total number of cutting tools in system is 50. In system configuration (c) if six machines produce part A and six produce part B, the total number of tools for twelve machines is 300. Accordingly, in configuration (B), number of needed tools is 100.

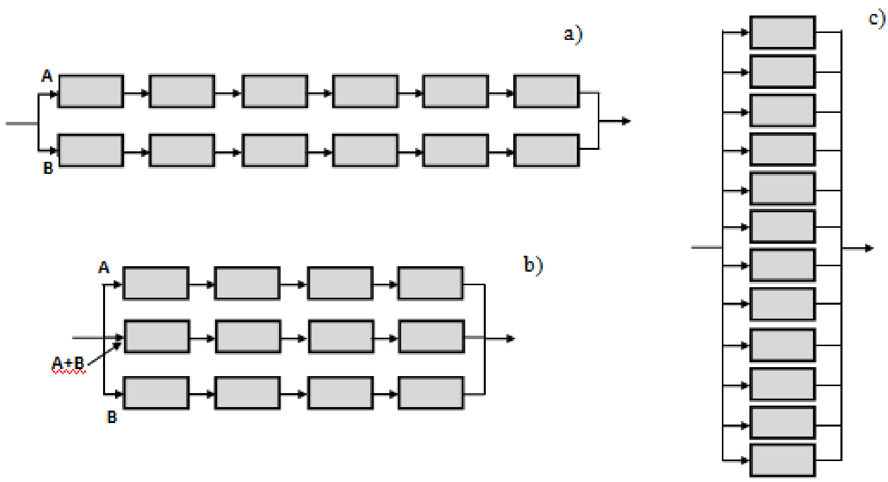


Fig. 2. Three example system configurations with twelve machines [5]

Let us also consider the impact of a single machine failures that continues more than a few hours (for example). In systems (a) and (b) below, the machining sequence is interrupted and the whole line loses productivity. If such an event causes the system, or a significant portion of it, to shut down the system is not adequately responsive.

The bottom row of Table 2 shows the percentage of throughput lost when such an event happens. Note in the configuration (a) 50% is a loss of the total production; similarly in configuration (b) 33,3% is a loss of the total production, why in the (c) configuration the loss is only 8,3%.

Tab. 2. The numbers of cutting tools needed in the systems and loss throughput of machine connected to presented configurations [5]

	Conf. (a)	Conf. (b)	Conf. (c)
Numbers of needed cutting tools	50	100	300
Loss of throughput if one machine is down	50%	33,3%	8,3%

Therefore, the choice of the best configuration is an optimal task taking into account the cost of cutting tools and reliability of machines. Moreover, selecting configuration, two measures of responsiveness – system convertibility and scalability should be considered as well. More information about problem of system's scalability can be found in [8].

5. PROBLEM OF MANUFACTURING PROCESSES SCHEDULING

The term "production scheduling" means determining the size of production batches and creating a detailed schedule (taking into account all the limitations). The aim of scheduling is the best use of enterprises resources and thereby competitiveness increase. The result of scheduling is developing a schedule of individual tasks (in the form of a chart or a description) [17].

Problems in creating production schedules also result from the fact that these problems belong to the class of NP-hard problems [12]. That means, the great difficulty in finding the exact solution – very long time necessary for the implementation of the algorithm. To illustrate the complexity of the general job-shop problem, consider a simple example (fig. 3).

Example. It is assumed that in a production process should be performed 5 production tasks. Each task should be done in 2 operations by means of 2 machines.

The number of operations to be scheduled: $5 \cdot 2 \cdot 2 = 20$

The number of all possible permutations: $20! = 2 \cdot 10^{18}$

Fig. 3. Example of complexity of the problem [18] [source: own study]

As we can see in the example, there are many possible permutations. In addition, finding the optimal solution among so many solutions is very troublesome.

During the planning of production assumes its static process, but usually in the production process various disturbances are appeared . Among the many changing factors we can distinguish: breakdowns of machines and robots, interferences associated with orders, interferences associated with tasks, incorrect estimate of the time of tasks, shortening or lengthening the time of tasks. Therefore, it is very important to prevent disturbances occurring in the production process. The more changes in the process, the greater his nervousness and disorganization. Even Henry Gantt (creator of the charts used in scheduling) used to say, that "the most elegant schedules created by planning offices are useless if they are ignored a situation that he observed" [11].

Therefore, using available tools and methods, we propose four-stages conception of robust scheduling in fig. 4 [18].

- Stage 1 – Production process data analyze (number of tasks, duration times of tasks, available machines) and creating the nominal production schedule. To create a schedule can be used appropriate methods of scheduling. For this purpose can be used LiSA software – computer program which helps creating schedules by mean of exact or heuristic algorithms. LiSA is abbreviation of "A Library of Scheduling Algorithms".
- Stage 2 – The use of historical data of the process to determine machines that could be damaged and tasks and tasks whose execution time may change. For this purpose we can use tool used to anticipating and predicting events – e.g. statistical analysis or artificial neural networks.
- Stage 3 – Creating a robust schedule with time buffers. Schedule will be created by adding time buffers in vulnerable areas of schedule – the application will find technique of redundancy.

- Stage 4 – The last stage of presented conception is robust schedule rating and comparing the quality of the nominal schedule with the robust schedule. In the case of achieve stated purpose robust schedule will be implemented. In the case of not achieve stated purpose – re-scheduling by means of other algorithm or detailed analysis of the parameters of considered disturbances.

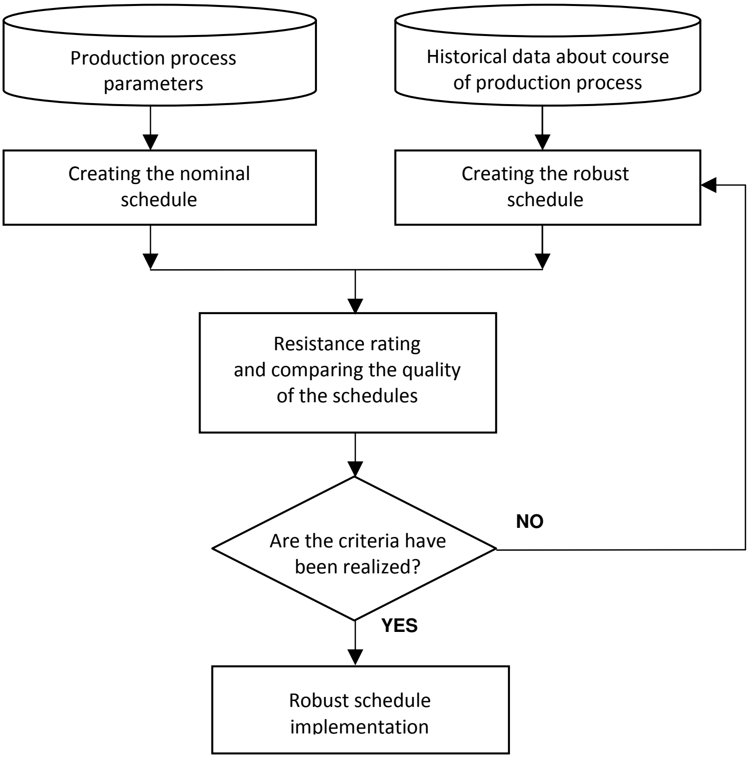


Fig. 4. Block diagram of robust scheduling [18]

6. CONCLUSIONS

Manufacturing companies in the 20th and the 21st century face increasingly frequent and unpredictable market changes driven by global competition, violent technical and technological development and constantly varying product demand. Consequently, both manufacturing methods and organization of manufacturing systems have changed during this time. The 20th century begins with craft manufacturing as only way of production.

Manufacturing systems design must provide effective solutions to cope with the demand during the whole system life-cycle. Therefore, this is critical task because it entails the consideration of different criteria related to economy, finance, technology, management, customer satisfaction and human resources involving both. Moreover, the impact of external uncertainty (e.g. demand volumes and technological characteristics of the products) and internal uncertainty (e.g. resource availability) should be taken into account during the design phase. As a consequence, the manufacturing system design problem must be concerned not only from the technological and organizational but also economical point of view.

From the scientific perspective, focusing the flexibility of a production system on the specific needs represents a challenging problem. Indeed, the customization of system flexibility provides economic advantages in terms of system investment costs, but on the other hand, tuning on the production problems reduces some of the safety margins which allow decoupling the various phases of manufacturing system design. Therefore, manufacturing system flexibility must be rationalized and it is necessary to find out the best trade-off between productivity and flexibility by designing manufacturing systems endowed with the right level of flexibility required by the production problem. In consequence, from the designer of modern manufacturing systems point of view it is very important to answer following questions:

- Are the conceptions of FFMS and RMS proper for modern companies?
- Which of conception – FFMS or RMS is much suitable for defined company?
- How to define the desired level of system's capacity?
- Which of the types of flexibility are the most important in the process of system design?
- How to forecast the way of development of manufactured parts?
- How to plan and optimize the cost of manufacturing system in its life-cycle?

REFERENCES

[1] ABELE E., LIEBECK T., WORN A.: *Measuring Flexibility in Investment Decisions for Manufacturing Systems.* Annals of the CIRP, vol. 55, issue 1, 2006, p. 433–436.

[2] BALÁŽ V., VAGAŠ M., HAJDUK M., SEJMON J.: *Modular Training System in Virtual Reality Environment – MSEVRT*, Applied Computer Science, vol. 9, no. 1, 2013, p. 46–53.

[3] CERYAN O., KOREN Y.: *Manufacturing capacity planning strategies.* CIRP Annals – Manufacturing Technology, vol. 58, 2009, p. 403–406.

[4] COCHRAN D.S., ARINEZ J.F., DUDA J.W., LINCK J.: *A decomposition approach for manufacturing system design*, Journal of Manufacturing Systems, no. 20(6), 2002, p. 371–389.

[5] GOLA A.: *Economical Aspects of Manufacturing Systems Design,* Actual Problems of Economics, no. 6 (156), 2014, p. 205–212.

[6] Gola A., Świć A.: *Computer Aided FMS Machine Tools Subsystem Selection – Conception of Methodology,* Applied Computer Science, vol. 5, no. 1, 2009, p. 27–39.

[7] GOLA A., ŚWIĆ A.: *Design of storage subsystem of flexible manufacturing system using the computer simulation method,* Actual Problems of Economics, no. 4 (142) 2013, p. 312–318.

[8] GOLA A., ŚWIĆ A.: *Economical Analysis of Manufacturing Systems Configuration in the Aspect of Their Productivity,* Actual Problems of Economics, no. 12 (162) 2014, p. 385–394.

[9] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*, [in:] R. Knosala (ed.) Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[10] HAJDUK M., JENČÍK P., JEZNÝ J., VARGOVČÍK L.: *Trends in industrial robotics development.* In: Applied Mechanics and Materials, vol. 282, 2013, p. 1–6.

[11] HERRMANN J. W.: *A history of production scheduling*, International Series in Operations Research & Management Science, vol. 89, 2006, p. 1–22.

[12] JENSEN M. T.: *Generating Robust and Flexible Job Shop Schedules Using Genetic Algorithms*, IEEE Transactions on Evolutionary Computation, vol. 7, no. 3, 2003, p. 275.

[13] KOREN Y.: *The Global Manufacturing Revolution.* Product-Process-Business Integration and Reconfigurable Manufacturing Systems, Wiley, New Jersey, 2010.

[14] KOREN Y. et al.: *Reconfigurable Manufacturing Systems*, Annals of the CIRP, vol. 48, no. 2, 1999, p. 527–540.

[15] KOREN Y., SHPITALNI M.: *Design of reconfigurable manufacturing systems*, Journal of Manufacturing Systems, vol. 29, issue 4, 2011, p. 130–141.

[16] LASKOWSKI D., ŁUBKOWSKI P., PAWLAK E., STAŃCZYK P.: *Anthropo-technical systems reliability, Safety and Reliability: Methodology and Applications,* Proceedings of the European Safety and Reliability Conference, ESREL 2014, 2015, p. 399–407.

[17] PAJĄK E.: *Zarządzanie produkcją – produkt, technologia, organizacja*, Wydawnictwo Naukowe PWN, Warszawa 2006 (in Polish).

[18] SOBASZEK Ł., GOLA A., ŚWIĆ A.: *Creating Robust Schedules Based on Previous Production Processes,* Actual Problems of Economics, no. 8 (158) 2014, pp. 488–495.

[19] SON Y.K., PARK C.S.: *Economic measure of productivity, quality and flexibility in advanced manufacturing systems,* Journal of Manufacturing Systems, no. 6(3), p. 193–207.

[20] STECKE K.E.: *Formulation and solution of nonlinear integer production planning problems for flexible manufacturing systems,* Management Science, no. 29(3), 1983, p. 273–288.

[21] STECKE K.E., SOLBERG J.*: Loanding control policies for a flexible manufacturing system,* International Journal of Production Research, No. 19(5), 1981, p. 481–490.

[22] TERKAJ W., TOLIO T., VALENTE A.*: Design of Focused Flexibility Manufacturing Systems* (FFMSs) [in]: Tolio T. (ed:) Design of Flexible Production Systems. Springer, 2009, p. 137–190.

[23] TERKAJ W., TOLIO T.: *An Approach to Production System Design Considering the Utility of the Machine Tool Builder,* 40th CIRP International Seminar on Manufacturing Systems, Liverpool, UK, 30 May-1 June 2007.

[24] United States Patent: *Reconfigurable Manufacturing System Having a Production Capacity Method for Designing Same And Method for Changing its Production Capacity,* Patent No.: US 6 349 237 B1, Date of Patent: 19th of February 2002.

[25] WANG W., KOREN Y.: *Scalability planning for reconfigurable manufacturing systems.* Journal of Manufacturing Systems, vol. 31, 2012, p. 83–91.

Juraj Kováč[1]

DESIGNING OF PRODUCTION SYSTEMS IN VIRTUAL ENVIRONMENT USING MULTI-TOUCH TABLE

1. INTRODUCTION

Designing of production processes and systems is a complex multilevel system, which is affected by numerous factors [3,8]. It specifies one of the primary activities in the preparation of innovation, modernization or restructuring of production [5]. Technological project is the first and fundamental model of structure of future production and is highly intellectually challenging, specifically aim-oriented activity [6]. Designing progress produces ideas, pictures and models of future production and also simulates future production process with its economic consequences. Design methods and techniques are constantly developed [2]. The current development is influenced mainly by the progress that is made in the information, communication and computer technologies. Technical support for project systems is using these technologies and it is an important innovation trend in design activity.

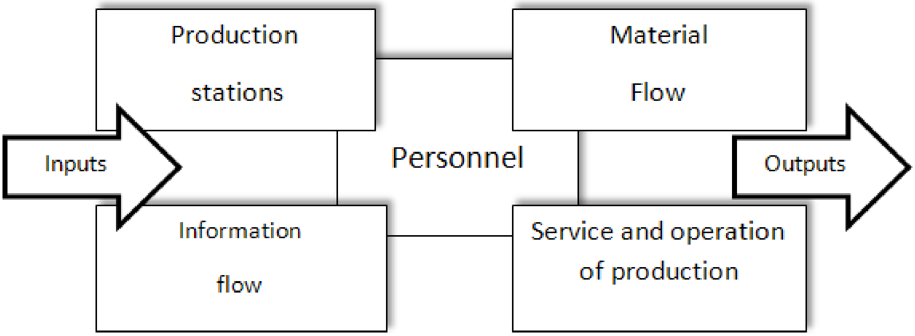


Fig. 1. Model of production system [1]

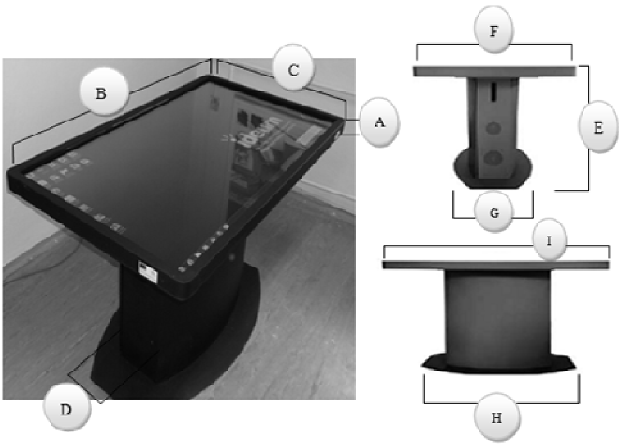
[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotics, Nemcovej 32, 042 00 Kosice, Slovak Republic e-mail: juraj.kovac@tuke.sk

2. INNOVATIVE APPROACHES TO DESIGNING OF PRODUCTION SYSTEMS

Modern scientific methods, processes and tools currently require the integration of design with specific software, information, communication and knowledge systems. Due to the intense innovation development and design of production systems and their clusters appear inspirational solutions that significantly affect the efficiency, quality and other parameters of the projects. Also the design in a virtual environment should respect the requirement for teamwork for each step of the proposal. This requires ensuring proper rendering partial outputs of design and the possibility of interactive, yet simple way to enter the draft and implement the changes, followed by the availability of feedback on what are the implications of the changes made to the basic parameters of the production layout. [4]

3. DESIGN OF PRODUCTION SYSTEMS BASED ON EQUIPMENT MULTI TOUCH TABLET

Fig. 2 represents Pro touch table 55"inch LED LCD touchscreen table with the powerful HP workplace-HD 32 + points of contact, UPA and integrated Yamaha audio system. Also dimensions and weight of the table is shown in Figure 2.



A	2"/51 mm
B	48"/1219 mm
C	27"/686 mm
D	8"/200 mm
E	31"/787 mm
F	295"/750 mm
G	215"/546mm
H	425"/1080 mm
I	505"/1283 mm

Fig. 2. Multi-touch Pro Table [7]

Benefits of design production station based on multi-touch tablet and software designer Factory are that they are stored in the database production equipment, peripherals and any funds that help manufacturing process. This design allows efficient production stations, robotic workplaces simple gesture marking the object from the database and transferring them on the desktop. This technology allows to design more efficient variants of arrangement of the layout of the workplace than with other technologies. Figure 3 shows the work in the design of production systems for based on multi-touch tablet. Project proposals can be changed in processing of different variations of 3D models, systems and resources. Designing requires adherence to certain principles. A process plant layout is in fact different.

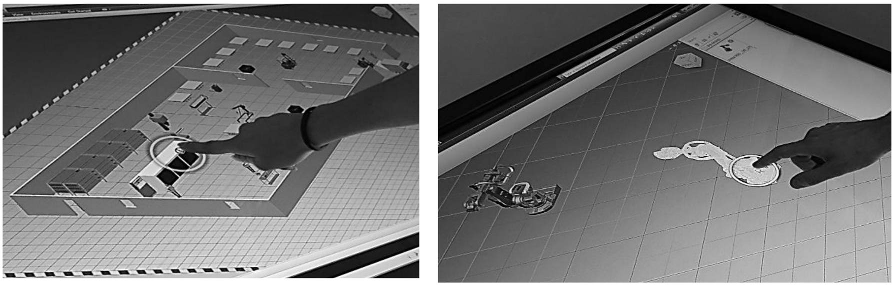


Fig. 3. Sample of projection for multi-touch tablet [7]

Intuitive interactive control logic generates the possibility of involvement of all interested specialists in the design process. This increases the quality of the design and effectiveness of the work of the project team. Procedure also applies to the creation of the whole factory. When applying such a method achieves several times more efficient and faster deployment of production equipment and facilities in the project.

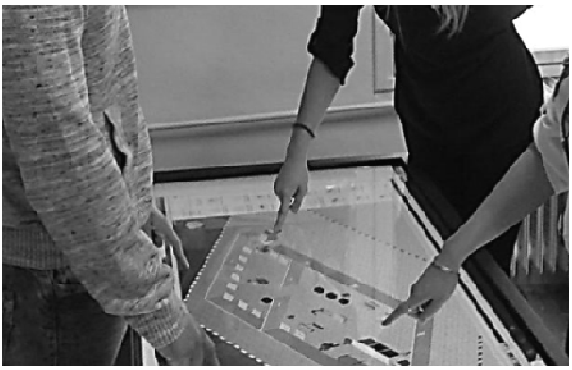


Fig. 4. Teamwork [7]

4. CONCLUSIONS

System knowledge and methodologies aimed at projection manufacturing systems need to be built as open for further development in terms of evolution and integration of new knowledge. A significant trend in the design, which increases the importance of an integrated sense of 3D modelling, it is necessary to consider the application software, information and communication technologies. Project into practice, it is necessary to introduce new design methodologies based on variant, interactive, innovative automated solutions.

Acknowledgements

The article was elaborated within the project VEGA 1/0102/1/0810/11 Principles of cooperation and profiling multi robotic systems.

REFERENCES

[1] BAUMRUK M.: *Ergonomické simulace podnikových procesů*. PLM journal, číslo 7, Duben 2006.

[2] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*. [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, s. 226–238.

[3] GOLA A., ŚWIĆ A.: *Intelligent decision support system for FMS machine tool subsystem design.* Applied Computer Science, vol. 3, no. 1, 2007, p. 109–124.

[4] KOVÁČ J., RUDY V., MAREŠ A., KOVÁČ J., MALEGA P.: *Integrated designing of production systems on the physical and virtual modelling base.* Acta Mechanica Slovaca. Roč. 16, č. 1 (2012), s. 30–40.

[5] KOVÁČ M., KOVÁČ J.: *Inovačné projektovanie výrobných procesov a systémov.* SjF TU v Košiciach, 2011.

[6] KRAJČOVIČ M., FURMANN R.: *Interaktívny systém projektovania výrobných dispozícií.* Produktivita a inovácie 1/2009.

[7] MAĎARIOVÁ M.: *Interaktívne metódy projektovania na báze využitia pracovného stola.* SjF TUKE, Košice, Diplomová práca, 2014.

[8] ŚWIĆ A., GOLA A.: *Elements of Design of Production Systems – Methodology of Machine Tool Selection in Casing-Class FMS.* Management and Production Engineering Review, vol. 1, no. 2, 2010, pp. 73–81.

Edward Kozłowski[1]

OPTIMAL STOPPING OF CONTROLLED LINEAR SYSTEM WITH QUADRATIC CRITERION

1. INTRODUCTION

The optimal control of stochastic systems with known and unknown parameters is well known (see e.g. [1], [7], [11], [12], [21], [24]). The aim of control consists in the optimization a performance criterion, which are depended on the states of system and controls. If the time horizon is established, then the designing of optimal controls for linear systems with quadratic cost LQC (Linear Quadratic control) is well known in the literature for both discrete and continuous time. If the parameters are unknown, then the optimal control process must enrich (increase) additionally the information about system parameters. In literature this problem is known as an adaptive control (see e.g. [2], [3], [11], [13], [14], [20], [21], [24]).

The horizon of control can be independent (completely external) as well as may depend on the system states. However, how to make the control law when the horizon is not fixed? The first case presents a situation, where the decision maker does not know the moment by which an object (economic, technical, social etc. system) may be controlled. He has only a'priori knowledge about the distribution of random horizon (see [17], [18]). Thus the random horizon doesn't depend on the behaviors of the system (the state of the system does not influence the horizon). In this case the horizon of control is modeled by a random variable state independent. The solution of this problem is based on construction of substitute task with established horizon (see e.g. [17], [18]). The second case concerns the problem of optimal stopping of random processes (see e.g. [8], [9], [15], [16], [23]). The solution consists in the Snell envelope construction and definition of stopping moment. The another method of solving this problem depend up construction an auxiliary task where the stopping problem is changed into control (see [4], [5]).

The paper presents the LQC problem with optimal stopping. In this work stopping problem is changed into control by introducing the binary variables. The optimal control and optimal stopping laws are given.

---

[1] Lublin University of Technology, Department of Quantitative Methods in Management, Poland, e-mail: e.kozlowski@pollub.pl

The organization of the paper is as follows. The section 2 presents the LQC problem with established horizon. The section 3 gives the modification of LQC problem with stopping to the task, where the stopping problem is replaced by additional control. The section 4 gives the optimal control and stopping law of linear system for auxiliary task. The simple applications of proposed approach are illustrated on two examples.

2. LINEAR QUADRATIC CONTROL PROBLEM

Let (Ω, F, P) be a complete probability space. Suppose that $m-$ dimensional random vectors $w_1, w_2, ...$ are independent identically distributed with normal distribution $N(0, I_m)$, y_0 be an initial state and N is a fixed horizon of control (the solution of the tasks where horizon of control is random is described in ….).

Let the system be described by the state equation

$$y_{i+1} = y_i + Cu_i + \sigma w_{i+1} \tag{1}$$

where $i = 0,1,2,....$, $C \in R^{nxl}$ and $\sigma \in R^{nxm}$. On (Ω, F, P) we define the family of $\sigma-$fields $Y_j = \sigma\{y_i : i = 0,1,..., j\}$. A Y_j-measurable vector $u_j \in R^l$ will be called a control action and $u = (u_0, u_1, u_2, ..., u_{N-1})$ an admissible control. The class of admissible controls is denoted by U . Let the functional $u_i^T Ru_i$ presents the cost of control at time i and the functional $y_N^T Qy_N$ presents the cost of heredity at the end of control (e.g. losses associated with system instability, no hit to target which is the origin of coordinate system).

To specify the aim of control we define the objective function as a sum of costs of controls and heredity at the end of horizon. Thus the objective function can be presented as

$$J(u) = E\left[\sum_{i=0}^{N-1} u_i^T Ru_i + y_N^T Qy_N\right]. \tag{2}$$

This function represents the composite costs and losses (CCL). The aim of optimal control is to minimize CCL

$$\inf_{u \in U} J(u) \tag{3}$$

and to determine a sequence of admissible control $u^* = (u_0^*, u_1^*, ..., u_{N-1}^*)$ for which the infimum is attained.

The solution of task (3) will be presented bellow. To determine the optimal control first we define the Bellman functions as

$$W_i^N(y_i) = \inf_{u_i} E\left(u_i^T R u_i + W_{i+1}(y_{i+1}) \middle| Y_i\right) \tag{4}$$

for $j = 0,1,...,N-1$ and $W_N^N(y_N) = y_N^T Q y_N$.

The optimal control of linear system (1) for the task (3) contains in follow

Theorem 1. If $\det\left(R + C^T K_i^N C\right) \neq 0$, where

$$K_i^N = K_{i+1}^N - \left(K_{i+1}^N\right)^T A_i K_{i+1}^N, \tag{5}$$

$$Z_i^N = tr\left(\sigma^T K_{i+1}^N \sigma\right) + Z_{i+1}^N, \tag{6}$$

$$A_i = C\left(R + C^T K_{i+1}^N C\right)^{-1} C^T$$

for $i = 0,..., N-1$ and $K_N^N = Q$, $Z_N^N = 0$, then the optimal control is

$$u_i^* = -\left(R + C^T K_{i+1}^N C\right)^{-1} C^T K_{i+1}^N y_i \tag{7}$$

and the least CCL value is equal

$$\inf_{u \in U} E\left(\sum_{i=0}^{N-1} u_i^T R u_i + y_N^T Q_N y_N\right) = W_0^N(y_0),$$

where

$$W_i^N(y_i) = y_i^T K_i^N y_i + Z_i^N. \tag{8}$$

Proof. At time $N-1$ the value of Bellman function is equal

$$\begin{aligned}
W_{N-1}^N(y_{N-1}) &= \min_{u_{N-1}} E\left(u_{N-1}^T R u_{N-1} + W_N^N(y_N) \middle| Y_{N-1}\right) \\
&= \min_{u_{N-1}} E\left(u_{N-1}^T R u_{N-1} + y_N^T Q y_N \middle| Y_{N-1}\right) \\
&= \min_{u_{N-1}} E\left(u_{N-1}^T R u_{N-1} + (y_{N-1} + C u_{N-1} + \sigma w_N)^T Q (y_{N-1} + C u_{N-1} + \sigma w_N) \middle| Y_{N-1}\right) \\
&= \min_{u_{N-1}} \left\{u_{N-1}^T \left(R + C^T Q C\right) u_{N-1} + 2 u_{N-1}^T C^T Q y_{N-1} + y_{N-1}^T Q y_{N-1} + tr\left(\sigma^T Q_N \sigma\right)\right\}
\end{aligned}$$

Thus the optimal control at time $N-1$ is

$$u_{N-1} = -\left(R + C^T Q C\right)^{-1} C^T Q y_{N-1}$$

and

$$W_{N-1}^{N}(y_{N-1}) = y_{N-1}^{T}(Q - QA_{N-1}Q)y_{N-1} + tr(\sigma^{T}Q_{N}\sigma).$$

Finally we have

$$W_{N-1}^{N}(y_{N-1}) = y_{N-1}^{T}K_{N-1}y_{N-1} + Z_{N-1}.$$

We assume that equation (8) is true for any time $i+1$. From (4) and the properties of condition expectation we have

$$\begin{aligned}
&W_{i}^{N}(y_{i}) = \min_{u_i} E\left(u_{i}^{T}Ru_{i} + W_{i+1}^{N}(y_{i+1}) \middle| Y_{i}\right) \\
&= \min_{u_{N-1}} E\left(u_{i}^{T}Ru_{i} + (y_{i} + Cu_{i} + \sigma w_{i+1})^{T} K_{i+1}^{N}(y_{i} + Cu_{i} + \sigma w_{i+1}) + Z_{i+1}^{N} \middle| Y_{i}\right) \\
&= \min_{u_{N-1}} \left\{u_{i}^{T}(R + C^{T}K_{i+1}^{N}C)u_{i} + 2u_{i}^{T}C^{T}K_{i+1}^{N}y_{i} + tr(\sigma^{T}K_{i+1}^{N}\sigma) + Z_{i+1}^{N}\right\}.
\end{aligned}$$

Thus, the optimal control at time i is

$$u_{i}^{*} = -(R + C^{T}K_{i+1}^{N}C)^{-1}C^{T}K_{i+1}^{N}y_{i}$$

and the value of Bellman function is equal

$$W_{i}^{N}(y_{i}) = y_{i}^{T}\left(K_{i+1}^{N} - (K_{i+1}^{N})^{T}A_{i}K_{i+1}^{N}\right)y_{i} + tr(\sigma^{T}K_{i+1}^{N}\sigma) + Z_{i+1}^{N}.$$

Finally, from (5)-(6) we obtain (8), which proves the assertion.

Remark 1. If horizon of control N is fixed, then using the control law (7) at times $i = 0,1,\dots,N-1$ to system (1) we get the lowest cost associated with controls and losses, when the system (1) is carried from point y_0 to the origin of coordinate system. On the other hand we see, that the total cost of controls and heredity $W_0^N(y_0)$ depend not only on initial state y_0 but also on horizon of control N.

3. THE OPTIMAL STOPPING OF LQC PROBLEM

In paper [6] the authors considered the relationship between total costs and horizon and it was shown that the artificial horizon setting is not the optimal decision because it can lead to additional costs. It may be a rational if the dynamic system will be stopped before the end of horizon of control, than the total cost may be lower. Thus, the task does not depend only on optimal control of system (1) but depend also on determining the optimal time to stop the stochastic system (1). The linear quadratic control problem with possible stopping of stochastic system (1) to time N we can present in the form.

$$\inf_{(u,\tau)} E\left[\sum_{i=-1}^{\tau-1} u_i^T R u_i + y_\tau^T Q y_\tau\right], \tag{9}$$

where: τ is a random variable defined on the probability space (Ω, F, P) and has realization on the set $\{0,1,\dots,N\}$. Of course, it may happen a such situation, where we do not control the system, then the time of optimal stopping is equal zero and we take $u_{-1} = col(0,\dots,0)$.

The optimal stopping of stochastic processes is very complicated mathematical task, which is a big challenge for researchers. The approach proposed in mathematical monographs usually based on the Snell envelope design (see e.g. [8], [9], [15], [16], [23]). This proves that the best time to stop is the first moment, where the dominated and stopped processes are equalized. However, in the considered task we does not stop only one process but the family of processes, which are indexed by control. This means we must make not only one Snell envelope but their entire family. Next we must select this one, for which obtained stopping time could give the optimal value of objective function.

The classical task of optimal stopping of stochastic processes requires the Snell envelope design (see e.g. [23]). In article [5] it was shown how to make the auxiliary task where the optimal stopping is replaced by additional control. This technique will be employed to the linear quadratic control problem with optimal stopping. To construct the auxiliary task of control we define additionally the variables θ_i with realizations in set $\{0,1\}$. Let the functions φ_i and ϕ_i are defined as

$$\varphi_i(\theta_1,\dots,\theta_i) = \prod_{j=1}^{i} \theta_j \tag{10}$$

and

$$\phi_i(u_i, y_i, \theta_i) = \theta_i u_i^T R u_i + (1-\theta_i) y_i^T Q y_i. \tag{11}$$

A Y_j-measurable process $\tilde{u} = (u, \theta)$ will be called an extended control action, where $u = (u_0, u_1, u_2, \dots, u_{N-1})$ is an admissible control, $\theta = (\theta_0, \theta_1, \theta_2, \dots, \theta_{N-1})$ is an admissible stopping, $u_j \in R^l$, $\theta_j \in \{0,1\}$. For $i = 0,1,\dots,N-1$ the variables θ_i have realizations 0 or 1. If the variable θ_i has realization 1, then the system (1) is controlled still. But if the variable θ_i has realization 0, then the system (1) must be stopped. Because the system may be controlled until time N, thus we assume $\theta_N = 0$. The linear quadratic control problem with optimal stopping can be presented in the form.

$$\inf_{\tilde{u}} J(\tilde{u}), \tag{12}$$

where the objective function is defined as

$$J(\tilde{u}) = E\left[\sum_{i=0}^{N-1} \phi_i(u_i, y_i, \theta_i) \prod_{j=1}^{i-1} \theta_j + y_N^T Q y_N \prod_{j=1}^{N-1} \theta_j\right]. \tag{13}$$

Thus we see, that in the task (12) the optimal stopping moment of controlled system (1) is the first moment when the variable θ_i has realization 0, i.e.

$$\tau = \min_{0 \le i \le N}(\theta_i = 0). \tag{14}$$

4. SOLUTION LQC PROBLEM WITH STOPPING

This section presents a determining of optimal control and stopping (optimal extended control) for linear system with quadratic criterion. To solve the task (12) (determine the optimal controls and stopping) we define the Bellman functions as

$$V_i\,(y_i) = \inf_{u_i, \theta_i} E\left(\theta_i u_i^T R u_i + (1-\theta_i) y_i^T Q y_i + \theta_i V_{i+1}(y_{i+1}) \middle| Y_i\right) \tag{15}$$

for $j = 0,1,\ldots,N-1$ and $V_N(y_N) = y_N^T Q_N y_N$. From above we obtain

$$\inf_{\tilde{u}} E\left[\sum_{i=0}^{N-1} \phi_i(u_i, y_i, \theta_i) \prod_{j=1}^{i-1} \theta_j + y_N^T Q y_N \prod_{j=1}^{N-1} \theta_j\right] = V_0(y_0).$$

The optimal controls and stopping of linear system (1) contain in theorem below.

Theorem 2. The optimal extended control (u_i, θ_i), $i = 0,1,\ldots,N-1$ of the system (1) for the task (12) is given

$$u_i^* = -\left(R + C^T K_{i+1}^k C\right)^{-1} C^T K_{i+1}^k y_i, \tag{16}$$

$$\theta_i = \begin{cases} 1, & \text{if } \; y_i^T Q y_i > \min\left(W_i^{i+1}(y_i), W_i^{i+2}(y_i), \ldots, W_i^N(y_i)\right) \\ 0, & \text{if } \; y_i^T Q y_i \le \min\left(W_i^{i+1}(y_i), W_i^{i+2}(y_i), \ldots, W_i^N(y_i)\right) \end{cases}, \tag{17}$$

where the value k satisfies the equation

$$W_i^k(y_i) = \min\left(W_i^{i+1}(y_i), W_i^{i+2}(y_i), \dots, W_i^N(y_i)\right),$$

and $W_i^k(y)$ is defined by (8). The value of Bellman function (15) is equal

$$V_i\ (y_i) = \min\left(y_i^T Q y_i, W_i^1(y_i), W_i^2(y_i), \dots, W_i^N(y_i)\right) \tag{18}$$

for $i = 0,1,\dots,N$.

Proof. At time $N-1$ the value of Bellman function is equal

$$\begin{aligned}
&V_{N-1}(y_{N-1}) = \\
&= \min_{u_{N-1},\theta_{N-1}} E\left((1-\theta_{N-1})y_{N-1}^T Q y_{N-1} + \theta_{N-1}\left(u_{N-1}^T R u_{N-1} + W_N(y_N)\right)\middle| Y_{N-1}\right) \\
&= \min_{\theta_{N-1}}\left((1-\theta_{N-1})y_{N-1}^T Q y_{N-1} + \theta_{N-1} \min_{u_{N-1}} E\left(u_{N-1}^T R u_{N-1} + y_N^T Q y_N \middle| Y_{N-1}\right)\right).
\end{aligned} \tag{19}$$

From theorem 1 the optimal control at time $N-1$ is

$$u_{N-1} = -\left(R + C^T Q C\right)^{-1} C^T Q y_{N-1}$$

and

$$\begin{aligned}
W_{N-1}^N(y_{N-1}) &= y_{N-1}^T(Q - QA_{N-1}Q)y_{N-1} + tr\left(\sigma^T Q \sigma\right) \\
&= y_{N-1}^T K_{N-1}^N y_{N-1} + Z_{N-1}^N
\end{aligned}$$

where K_{N-1}^N, Z_{N-1}^N are given by (5)-(6) suitable. From above the value $V_{N-1}(y_{N-1})$ is given by equation (15) and may be presented in form

$$V_{N-1}(y_{N-1}) = \min_{\theta_{N-1}}\left((1-\theta_{N-1})y_{N-1}^T Q y_{N-1} + \theta_{N-1} W_{N-1}^N(y_{N-1})\right). \tag{20}$$

Solving the task (20) we have

$$\theta_{N-1} = \begin{cases} 1, & \text{if } \ y_{N-1}^T Q y_{N-1} > W_{N-1}^N(y_{N-1}) \\ 0, & \text{if } \ y_{N-1}^T Q y_{N-1} \le W_{N-1}^N(y_{N-1}) \end{cases}.$$

We see, that the system (1) must be stopped (the variable $\theta_{N-1} = 0$) if the value heredity function at time $N-1$ (the value $y_{N-1}^T Q y_{N-1}$) is not greater than sum cost of control at this time $N-1$ and heredity cost at next time N (the value of Bellman function $W_{N-1}^N(y_{N-1})$). If the value heredity function at time $N-1$

(the value $y_{N-1}^T Q y_{N-1}$) is more than sum cost of control at this time $N-1$ and heredity cost at next time N (the value of Bellman function $W_{N-1}^N(y_{N-1})$), than the system (1) must be controlled still and the variable $\theta_{N-1}=1$. Finally we have

$$\theta_{N-1}=\begin{cases}1, & \text{if } W_{N-1}^{N-1}(y_{N-1})>W_{N-1}^{N}(y_{N-1})\\ 0, & \text{if } W_{N-1}^{N-1}(y_{N-1})\le W_{N-1}^{N}(y_{N-1})\end{cases}.$$

Finally the value of Bellman function $V_{N-1}(y_{N-1})$ may be presented as

$$V_{N-1}(y_{N-1})=\min\{W_{N-1}^{N-1}(y_{N-1}),W_{N-1}^{N}(y_{N-1})\}.$$

We assume that equation (18) is true for any time $i+1$. From (15) and the properties of condition expectation we have

$$V_i\ (y_i)=\min_{u_i,\theta_i} E\left((1-\theta_i)y_i^T Q y_i+\theta_i\left(u_i^T R u_i+V_{i+1}(y_i)\right)\middle|Y_i\right)$$
$$=\min_{\theta_i}\left((1-\theta_i)y_i^T Q y_i+\theta_i\min_{u_i} E\left(u_i^T R u_i+\min\left(W_{i+1}^{i+1}(y_i),\ldots,W_{i+1}^{N}(y_i)\right)\middle|Y_i\right)\right)$$

Employing the results of theorem 1 we obtain, that the optimal control at time i is

$$u_i^*=-\left(R+C^T K_{i+1}^k C\right)^{-1}C^T K_{i+1}^k y_i,$$

where k we obtain from equation

$$W_i^k(y_i)=\min\left(W_i^{i+1}(y_i),W_i^{i+2}(y_i),\ldots,W_i^N(y_i)\right)$$

From above the value $V_i\ (y_i)$ is given by equation (15) and may be presented in form

$$V_i\ (y_i)=\min_{\theta_i}\left((1-\theta_i)y_i^T Q y_i+\theta_i\min\left(W_i^{i+1}(y_i),W_i^{i+2}(y_i),\ldots,W_i^N(y_i)\right)\right) \quad (21)$$

Solving the task (21) we have

$$\theta_i=\begin{cases}1, & \text{if } y_i^T Q y_i>\min\left(W_i^{i+1}(y_i),W_i^{i+2}(y_i),\ldots,W_i^N(y_i)\right)\\ 0, & \text{if } y_i^T Q y_i\le\min\left(W_i^{i+1}(y_i),W_i^{i+2}(y_i),\ldots,W_i^N(y_i)\right)\end{cases}.$$

We see, that the system (1) must be stopped (the variable $\theta_i = 0$) if the value heredity function at time i (the value $y_i^T Q y_i$) is not greater than possible composite costs in future (if the system be stopped in possible times $i+1,...,N$). If the value heredity function at time i (the value $y_i^T Q y_i$) is more than possible composite costs in future, than the system (1) must be controlled still and the variable $\theta_i = 1$. Finally we have

$$\theta_i = \begin{cases} 1, & \text{if } W_i^i(y_i) > \min\left(W_i^{i+1}(y_i), W_i^{i+2}(y_i), ..., W_i^N(y_i)\right) \\ 0, & \text{if } W_i^i(y_i) \le \min\left(W_i^{i+1}(y_i), W_i^{i+2}(y_i), ..., W_i^N(y_i)\right) \end{cases}.$$

Thus the value of Bellman function (15) at time $0 \le i \le N-1$ is defined as

$$V_i(y_i) = \min\left(W_i^i(y_i), W_i^{i+1}(y_i), W_i^{i+2}(y_i), ..., W_i^N(y_i)\right),$$

which proves the assertion.

Corollary 1. The optimal moment τ when the controlled system (1) must be stopped, it is the first moment when the value of heredity function $y_\tau^T Q y_\tau$ is not greater than possible costs of controls and heredity in future

$$y_\tau^T Q y_\tau \le W_\tau^k(y_\tau) \text{ for } k = \tau+1,...,N.$$

In other words, if we will continue the system control then we will incur additional costs than we stop the system.

Example 1. Let the linear system be described by the state equation (1) and the initial position of system is $y_0 = \begin{pmatrix} 20 \\ 30 \end{pmatrix}$. We assume that the stochastic system may be controlled up to time $N = 20$ and

$$Q = \begin{bmatrix} 9.4 & 0.3 \\ 0.2 & 22 \end{bmatrix}, \ R = \begin{bmatrix} 1.8 & 0 \\ 0 & 0.9 \end{bmatrix}, \ C = \begin{bmatrix} 0.2 & 0.3 \\ -0.3 & 0.8 \end{bmatrix}, \ \sigma = \begin{bmatrix} 1.5 & 0 \\ 0 & 1 \end{bmatrix}$$

The system (1) must be removed from initial state y_0 to origin of coordinates system at lowest cost. We determine the optimal controls and stopping moment.

To determine the optimal controls and stopping moment we employ the results of theorem 2 and corollary 3. The value $H(y_i) = y_i^T Q y_i$ for $i = 0,...,N-1$ presents the heredity value if the system must be stopped at time i.

From corollary 3 we see, that the optimal moment of stopping τ is a moment where the heredity function $H(y_\tau)$ and Bellman function $V(y_\tau)$ are equal. The table below presents the system states y_i, controls u_i, heredity values $H(y_i)$ and values of Bellman function $V_i(y_i)$. In this case the stochastic system cannot be controlled to end of horizon $N = 20$ but must be stopped at time $\tau = 9$.

Tab. 1. The simulations of system states y_i, controls u_i, heredity values H_i and values of Bellman function V_i for $i = 0,1,\ldots,\tau$ [source: own study]

i	y_i	H_i	V_i	*Action*	u_i
0	*(20,30)*	*23860*	*310.81*	*System must be controlled*	*(-4.39,-10.7)*
1	*(13.67,23.34)*	*13898.68*	*219.6*	*System must be controlled*	*(-2.43,-7.99)*
2	*(10.92,17.43)*	*7900.2*	*191.77*	*System must be controlled*	*(-2.18,-6.09)*
3	*(9.48,12.62)*	*4411.22*	*181.14*	*System must be controlled*	*(-2.4,-4.69)*
4	*(7.32,7.97)*	*1932.68*	*161.8*	*System must be controlled*	*(-1.36,-1.35)*
5	*(6.85,7.15)*	*1590.82*	*156.44*	*System must be controlled*	*(-1.29,-1.23)*
6	*(2.28,4.01)*	*406.89*	*71.28*	*System must be controlled*	*(-0.2,-0.31*
7	*(3.25,3.05)*	*309.26*	*90.08*	*System must be controlled*	*(-0.45,-0.26)*
8	*(2.83,1.81)*	*150.18*	*80.48*	*System must be controlled*	*(-0.47,-0.18)*
9	*(2.5,0.8)*	*73.896*	*73.896*	*System must be stopped*	-----------

Example 2. The stochastic system (1) must be removed from this same initial state y_0 as ex ample 1 to origin of coordinates system at lowest cost. We assume that the stochastic system may be controlled at the times $0,1,\ldots,19$ (the horizon of control is $N = 20$) and

$$Q = \begin{bmatrix} 0.7 & 0.03 \\ 0.03 & 0.2 \end{bmatrix},\ R = \begin{bmatrix} 0.25 & 0 \\ 0.2 & 0.9 \end{bmatrix},\ C = \begin{bmatrix} 0.2 & 0.3 \\ -0.3 & 0.8 \end{bmatrix},\ \sigma = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.2 \end{bmatrix}.$$

In this case the system (1) must be controlled to the end of horizon, because only at the end of horizon the values of heredity and Bellman function are identically.

The picture 1.a presents the values of heredity function $H(y_i) = y_i^T Q y_i$ (blue curve) and values of Bellman function $V_i(y_i)$ (red curve, defined by equation (15)) for moments $0,1,\ldots,20$. The picture 1.b presents the differences between heredity functions $H(y_i)$ and values of Bellman functions $V_i(y_i)$

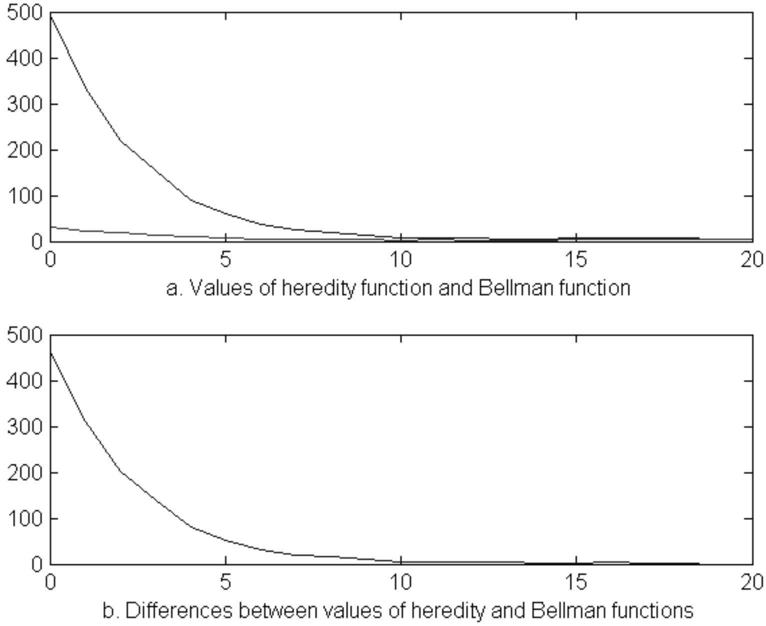


Fig. 1. The graphs of values of heredity and Bellman functions and differences between them [source: own study]

5. CONCLUSIONS

In this article, the linear quadratic control with stopping problem was introduced and the laws of control and stopping were worked out. To determine the optimal stopping did not employed the Snell envelope. The stopping problem was replaced by additional control, which was modeled by a binary variables.

The simple simulation shows that sometimes it pays to stop the system before the end of horizon of control (because we may have the lowest costs of control). Thus in classical tasks the artificial horizon setting is not the optimal decision because it can lead to additional costs.

REFERENCES

[1] AOKI M.: *Optimization of Stochastic Systems*, Academic Press, New York, 1967.

[2] BANEK T., KOZŁOWSKI E.: *Adaptive control of system entropy*. Control and Cybernetics 35 (2), 2006, p. 279–289.

[3] BANEK T., KOZŁOWSKI E.: *Active and passive learning in control processes application of the entropy concept.* Systems Sciences 31 (2), 2005, p. 29–44,.

[4] BANEK T., KOZŁOWSKI E.: *Adaptive control with random horizon.* Annales Informatica 3, 2005, p. 5–14.

[5] BANEK T., KOZŁOWSKI E.: *Adaptacyjne sterowanie terminalne z losowym horyzontem,* materiały XV Krajowej Konferencji Automatyki, tom I, 2005, p. 257–261.

[6] BANEK T., KOZŁOWSKI E.: *Deterministic versus stochastic in the free horizon LQC problem*, materiały XVIII Krajowej Konferencji Automatyki, 2014.

[7] BELLMAN R.: *Adaptive control processes*, Princeton, 1961.

[8] BENTH F. E., REIKVAM K.: *A Connection between Singular Stochastic Control and Optimal Stopping.* Applied Mathematics and Optimization 49, 2004, p. 27–41.

[9] BOETIUS F., KOHLMANN M.: *Connections between optimal stopping and singular stochastic control.* Stochastic Processes and their Applications 77, 1998, p. 253–281.

[10] CHENA Y., EDGARB T., MANOUSIOUTHAKIS A. V.: *On infinite-time nonlinear quadratic optimal control.* Systems & Control Letters 51, 2004, p. 259–268.

[11] FLEMING W. H., RISHEL R.: *Deterministic and stochastic optimal control*, Springer-Verlag, Berlin, 1975.

[12] FELDBAUM A. A.: *Optimal Control Systems*, Academic Press, 1965.

[13] HANSON B. F.: *Applied stochastic processes and control for jump – diffusions. Modelling, analysis and computation*, SIAM, Philadelphia, 2007.

[14] HARRIS L., RISHEL R.: *An algorithm for a solution of a stochastic adaptive linear quadratic optimal control problem.* IEEE Transactions on Automatic Control 31, 1986, p. 1165–1170.

[15] KARATZAS I., SHREVE S. E.: *Connections between optimal stopping and singular control I. Monotone follower problems.* SIAM Journal Control and Optimization 221984, p. 856–877.

[16] KARATZAS I., SHREVE S. E.: *Connections between optimal stopping and singular control II.* Reflected follower problems. SIAM Journal Control and Optimization 23, 1985, p. 433–451.

[17] KOZŁOWSKI E.: *Discrete time stochastic control with random finite horizon*. Ed. Tadeusz Banek, Process Control in Management, Toruń, 2009, p. 53–66.

[18] KOZŁOWSKI E.: *Optymalne sterowanie liniowo-kwadratowe z losowym horyzontem o rozkładzie Poissone'a,* materiały VII Krajowej Konferencji Automatyki, 2011, p. 105–117.

[19] LIPTSER R. SH., RUNGGALDIER W. J., TAKSAR M.: *Deterministic approximation for stochastic control problems.* SIAM Journal Control and Optimization 34, 1996, p. 161–178.

[20] RISHEL R.: *A nonlinear discrete time stochastic adaptive control problem.* Theory and applications of nonlinear control systems, Sel. Pap. 7th Int. Symp. Math. Theory Networks Systems, 1985, p. 585–592.

[21] RUNGGALDIER W. J.: *Concepts and methods for discrete and continuous time control under uncertainty.* Insurance Mathematics and Economics 22, 1998, p. 25–39.

[22] SARIDIS G. N.: *Stochastic processes estimation and control: the entropy approach*, John Wiley& Sons, 1995.

[23] SHIRYAEV A. N.: *Statistical analysis of sequential processes. Optimal stoppping rules*, Springer-Verlag, New York, 1978.

[24] ZABCZYK J.: *Chance and decision*, Scuola Normale Superiore, Pisa, 1996.

Viera Kyseľová

INNOVATIVE INDUSTRIAL POLICY IN EUROPEAN UNION AND ROBOTICS

1. INNOVATIVE INDUSTRIAL POLICY

Qualitative changes happening in the global economy are reflected also in the field of industrial policy [3]. The main priority of the Member States of the European Union became the promotion of growth and competitiveness in order to strengthen the recovery in the area of industry [2,5,7].

In order to achieve these objectives, the European Union seeks to establish the legal and institutional environment conducive to the European industry, so that with innovations supporting the increasing of quality and use of new technologies, it has become an integral and important part of the global economy.

Innovative industrial policy of the European Union supports the restructuring of the industry and stimulates competitiveness of new industry sectors. An important pillar of improved competitiveness is the integrated approach to industrial policy, based on the work program of horizontal and sectoral initiatives, which has to stimulate the efforts of the European Union to ensure the proper functioning of the internal market, as well as open and competitive global markets [1].

Strategic materials for the creation and management of industrial policy of the European Union is the EC Treaty, which enshrines the following objectives:

- Speeding up the adjustment of the industry to structural changes;
- Support an environment that is supportive to the creation and development of enterprises throughout the Community, particularly small and medium-sized enterprises;
- Encouraging an environment favourable to cooperation between enterprises;
- Help in better utilization of the industrial potential of innovation, research and technological development.

The main objective of European industrial policy is to promote the integration of sustainable development with a tendency to actively promote competetiveness in the Community, with priority at establishing the framework conditions for business development and innovation.

An integral part of the industry is the area of industrial automation and robotics, which is experiencing expansive growth. The rapid development of technologies and their deployment in various industries paves the way for robotics, which has its irreplaceable place.

According to a study made by IFR (International Federation of Robotics) "World Robotics 2014 – Industrial Robots", the increased demand for industrial robots should continue as seen in Figure 1. In 2014, the worldwide installation of more than 200,000 industrial robots is expected, which in comparison with 2013 represents an increase by 15%, and in the coming years 2015-2017 demand is expected to grow by an average of 12% per annum [4].

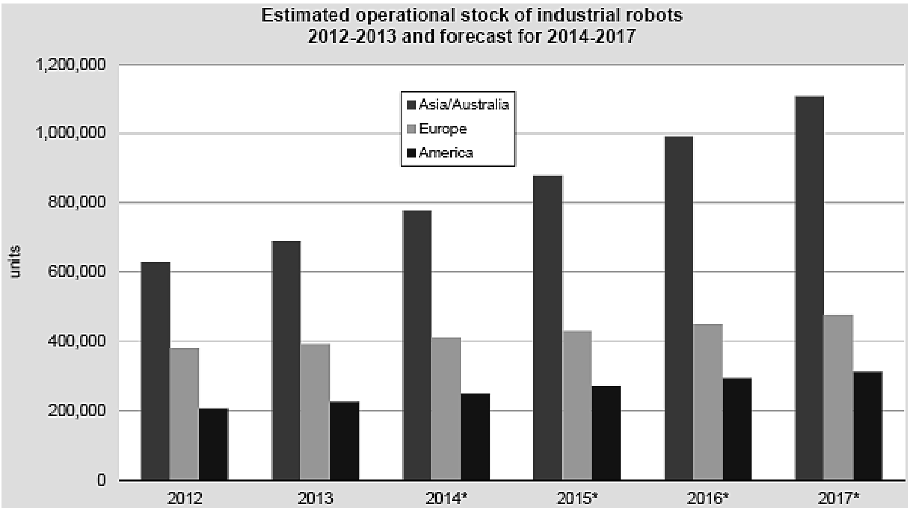


Fig. 1. Estimated operational stock of industrial robots 2012-2013 and forecast for 2014-2017 (marked as *)

1.1 Industrial automation and robotics

Industry is one of the most important economic sectors in Slovakia [8]. The key to market success in the manufacturing process are productivity and competetiveness. The solution is robotics and automation.

Robotics – represents a cluster of technological equipment, industrial robots, manipulators, conveyors and other devices that are autonomously, in an automated cycle, carrying out handling or technological operations of the production process, or just parts of it.

Industrial robots – are characterized as electromechanical system that is able to grasp, transport, machine and where applicable assemble objects. They represent a universal machine performing movements similar to the movements of a human hand or arm.

The main advantages of robotics are:

Reducing operating costs:

- Robotics helps to reduce production and operation costs;
- Robotics reduces the costs associated with employees (salaries and payroll, social and health insurance costs, holidays and sickness, eliminates the costs of recruitment, courses and staff training, the purchase of protective equipment, the administrative staff and other...);
- Requirements for lighting and heating are reduced, resulting in high energy cost savings.

Quality and limiting material losses:

- Robotics results in stable technological processes, ensures continuous visibility and control over the production process. The high and repeatable quality of products ensures high yields and reduces costs associated with scrap and material losses.
- Robotics results in the stabilization of the technological process, eliminating downtime, errors and deviations caused by human factors such as fatigue, inattention, inconsistency or effects associated with monotonous and repetitive work.
- Accuracy of robots and the possibilities of off-line programming ensure by some technological processes (gluing, welding, painting, etc.) high-speed, stability and high final product quality.

Productivity:

- The deployment of robots in serial or mass production is many case a matter of course. The robot can work 24 hours a day, 7 days a week, on a continuous basis, with minimal supervision;
- Acceleration of the production process;
- Real 24 hour production of robotic workstation increases business productivity and ensures compliance with the deadlines required by customers;
- The changes caused by human factor are eliminated, for example. interruption of production due to illness, fatigue and decreased concentration of workers, etc. ;
- With off-line robot programming, it can be flexible to introduce new products into production and launch a new production without interrupting production processes.

Flexibility:

- Robotics enables rapid and flexible response to changing requirements of production and customers;
- Using sensors and intelligent camera systems the workplace can be adapted for a variety of products, processes and applications;
- Robot allows for more flexibility in the production line;
- If different processes are programmed into the robot control unit, it is possible to easily switch between them and select for each product its own program. This makes it possible to automate a small batch and unit production.

Safety:

- The robot takes unpleasant, strenuous, monotonous, health and life-threatening tasks, thereby increasing the safety and health of workers;
- Robotics reduces the likelihood of accidents and injuries caused by contact with the machines, instruments and other hazards in the production process;
- Helps to reduce staff diseases caused by repeated or arduous work.

Saving the workspace:

- The robot can be installed on a pedestal in hanging position on the ceiling, on the wall or on the machine, in order to maximize the designated work area;
- The robot can be programmed to operate in confined space and to use minimum of working space;

Better working environment for staff:

- The robot takes over work tasks that require working in hazardous environment where strong pollution, noise and extreme temperatures are present;
- Improving working conditions for employees;
- Motivation of employees to a better and more interesting work such as retraining to operate the robots.

High efficiency and return on investment:

- Robotics reduce operating costs and production costs, scrap and space requirements, but increase productivity and quality;
- Reduction of manual work means less expenditures on sickness, accidents and insurance costs.

REFERENCES

[1] *10 důvodu proč investovat do průmyslových robotů,* Vše o průmyslových robotech. [online: http://www.roboti.cz/proc-investovat-do-robotu].

[2] *Consolidated versions of the treaty on European Union and of the treaty establishing the European community,* Official Journal of the European Union C 321 E/1 [online: https://www.ecb.europa.eu/ecb/legal/pdf/ce32120061229sk00010331.pdf].

[3] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*, [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[4] HRANKA Š.: *Robotizácia: Nezastupiteľné miesto pri znižovaní nákladov na výrobu,* BOST: Automatizácia 2009, [online: http://automatizacia.bost.sk/uploaded/automatizacia/ 2009-bt-robotizacia.pdf].

[5] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A.: *A predictive model of multi-stage production planning,* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[6] SMRČEK J., HAJDUK M., BOBOVSKÝ Z., JÁNOŠ R.: *Robotika – Metodika nasadzovania servisných robotov,* Technická univerzita v Košiciach, 2013.

[7] SOBASZEK Ł, GOLA A., ŚWIĆ A.: *Creating Robust Schedules Based on Previous Production Processes,* Actual Problems of Economics, no. 8 (158) 2014, p. 488–495.

[8] *World Robotics:Industrial Robots 2014,* International Federation of Robotics. [online: http://www.ifr.org/news/ifr-press-release/accelerating-demand-for-industrial-robots-will-continue-658].

Jozef Varga[1]

MOBILE APPLICATION FOR CONTROLLING SOCCER ROBOTS

1. MAIN FUNCTION OF APPLICATION

In this paper is described a development of Android application for controlling of robosoccer robots via Bluetooth interface. Application is created at online development environment MIT app inventor 2.

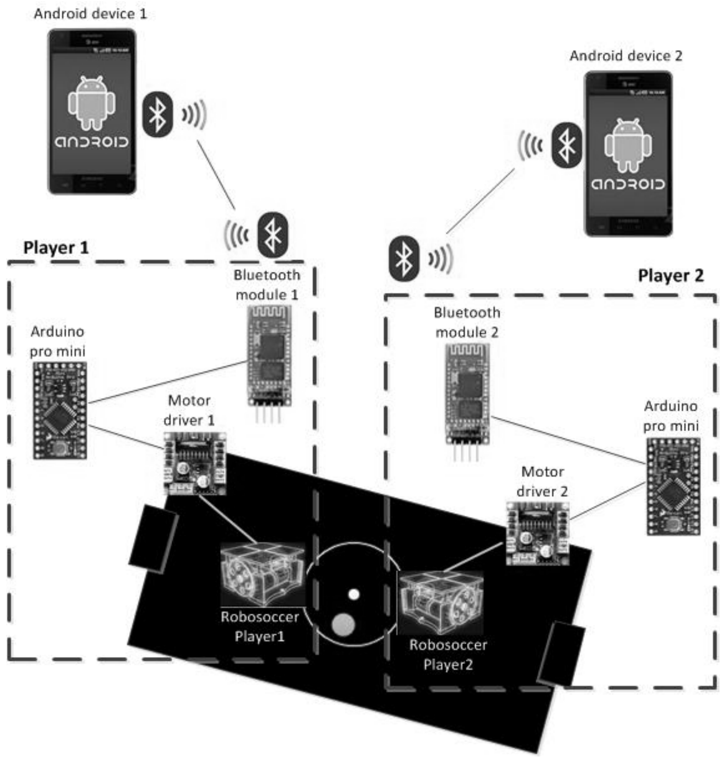


Fig. 1. Interconnection of devices [source: own study]

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotic, Letna 9, 04200, Košice, Slovakia, e-mail: jozef.varga.2@tuke.sk

Android device is sending data to Bluetooth module into the robot and Arduino pro mini controlling dc motors to robot via PWM motor driver from Bluetooth receiving data, figure 1. After the start application users can choose from connection to Player 1 or Player 2 robot. Application then initialize screen for control of robot and turn on Bluetooth on device [2,3,6,9]. In Bluetooth settings is necessary pairing android device with arduino module and then pressing START button for connecting to robosoccer player [4,7]. Direction of robot is controlling via accelerometer and speed via movement slider [1,5,8]. Maximal speed of robot is 4 meter per second.

2. HOME SCREEN OF ROBOSOCCER APPLICATION

At figure 2(a) is shown home screen1 of application, which allows choose from two players. The source of commands at MIT app inventor 2 was created by block schemes. At figure 2(b) are shown blocks for initialization of next action. After the pressing of button Player1 will open screen2 or Player2 open screen3.

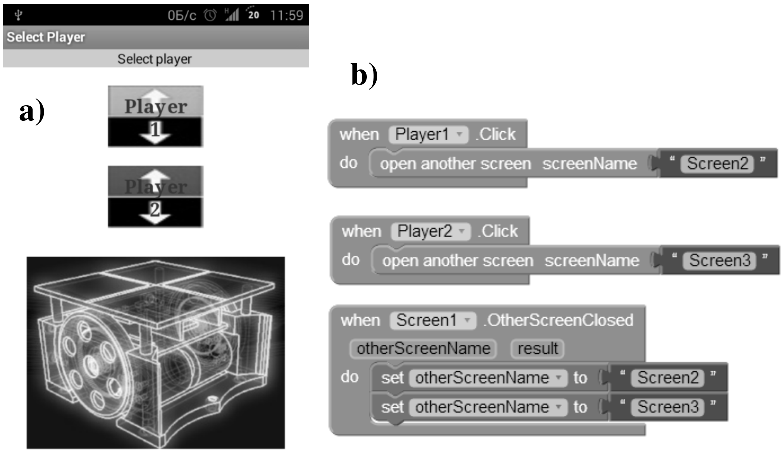


Fig. 2. (a) Home screen; (b) Block schemes of home screen [source: own study]

Bluetooth enable the activity starter for turning on Bluetooth is call after initialization Screen2, that is shown at figure 3. This same activity starter will call after initialization Screen3.

Fig. 3. Call activity starter for turning at Bluetooth [source: own study]

3. SCREENS AND BLOCK SCHEMES FOR ROBOT CONTROL

Screens at figure 4 consist from Bluetooth paired Player button and from START button for Bluetooth connection into the robot. In the middle is image sprite of robot for monitoring direction and at the lower side are displayed values of accelerometer X and Y. At right side of screen is slider for speed control.

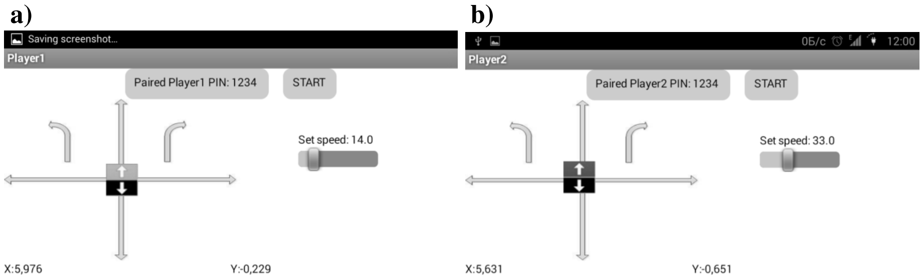


Fig. 4. (a) Screen2 for Player1; (b) Screen3 for Player2 [source: own study]

By pressing of paired button we can call Bluetooth settings via activity starter that is shown on blocks at figure 5, for pairing of android device with robot. Button START is used for connecting device to Bluetooth module which address into the robot and also for activating of Clock 1 and Clock 2 for sending data.

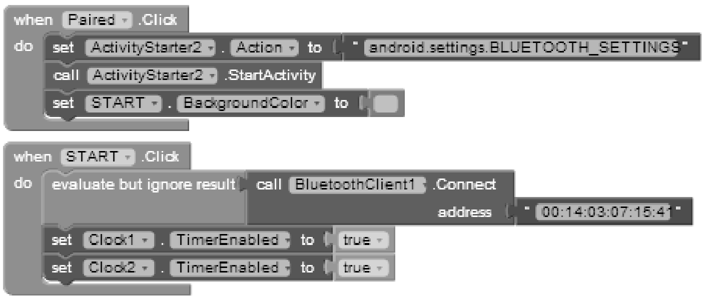


Fig. 5. Block schemes of buttons for Paired and START [source: own study]

For sending data from android device to robot was creating two variables: slider and direction, shown at figure 6. Direction is variable that is using for determination of robot direction and slider variable is using for determination of robot speed.

Fig. 6. Create of slider and direction variables [source: own study]

3.1. Algorithm for sending data of acceleration sensor

Algorithm that is shown at figure 7 is using for sending data about tilting of android device and determined of zero position. On the base of this data is possible to determine direction of robot movement.

Fig. 7. Algorithm for sending data of acceleration sensor [source: own study]

3.2. Algorithm for sending data of acceleration sensor

Algorithm shown at figure 8 is used for slider variable assignment of thumb position. On the base of this data is set speed of robot.

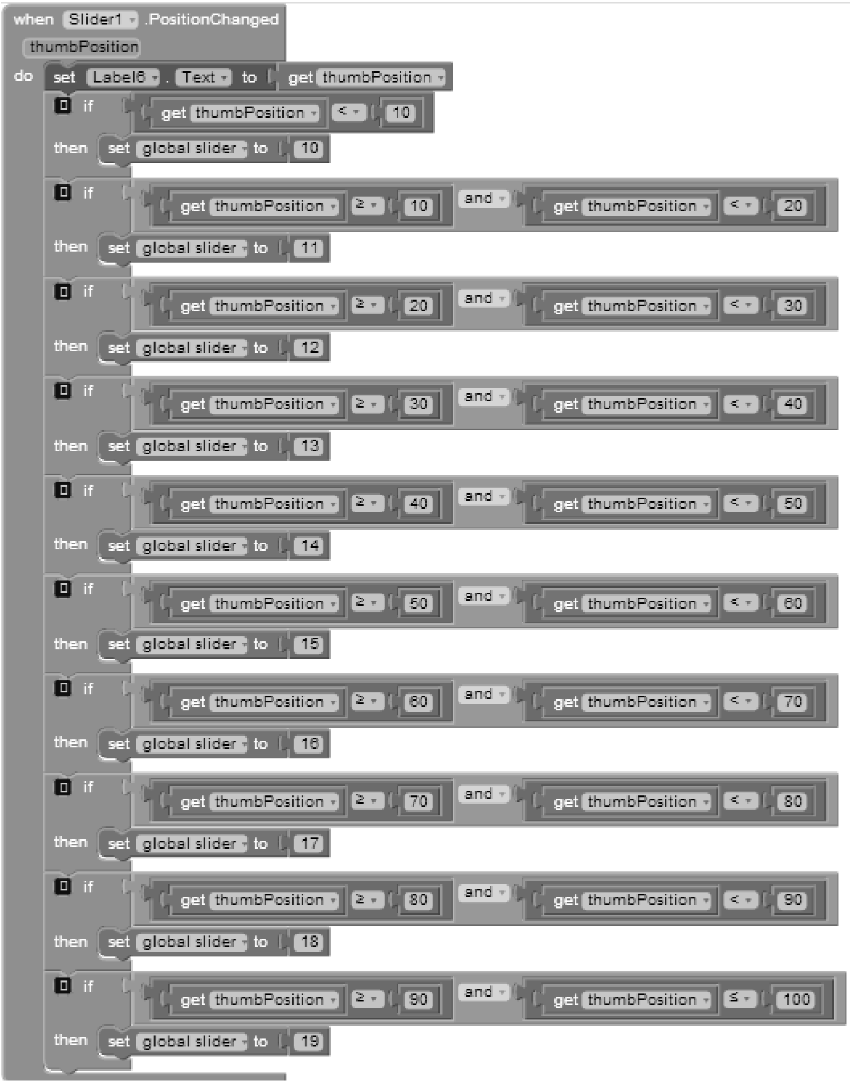


Fig. 8. Algorithm for sending data of slider [source: own study]

3.3. Algorithm for sending data of acceleration sensor

Clock1 is sending data from direction variable and Clock2 is sending data from slider variable, block scheme is shown at figure 9.

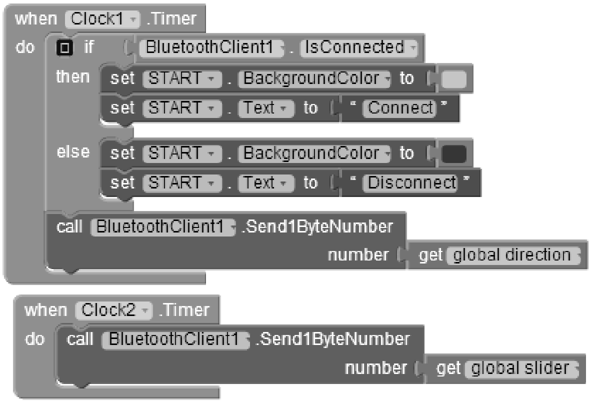


Fig. 9. Sending data of slider and direction variables [source: own study]

For closing of application is used back button of device. After the pressing of back button was call the stop for sending data from Clock1 and Clock2 and then follows closing of application, shown at figure 10.

Fig. 10. Block schemes for back button pressed [source: own study]

4. CONCLUSIONS

This application describes an implementation of android application that was created at MIT app inventor 2 for controlling of robosoccer players, made by Department of robotics SjF TUKE. Connection between android device and arduino at robot is realized by Bluetooth interface. Users can download application from Google play store – Robosoccer. After starting of application users can choose from controlling green picture – Player 1 or blue picture – Player 2 robot. Robosoccer can play two users between themselves with android device. This application can be extended with more robots and it can be used for controlling with other types of robots.

Acknowledgements

This contribution is the result of the project implementation: KEGA 059TUKE-4/2014 "The Development of quality of life, creativity and motor functionalities of disabilities and older people with support of robotic devices."

REFERENCES

[1] BENIAK J.: *Rapid prototyping and accuracy of created models.* ERIN, Roč. 5, č. 6 (2012), p. 2–8.

[2] BENIAK, JURAJ-KRIŽAN, PETER-MATÚŠ, MILOŠ: *Accuracy of Rapid Prototyped models with using of FDM technology.* In: Applied Mechanics and Materials, vol. 613, 2014, p. 390–395.

[3] GOLA A., SOBASZEK Ł.: *Simulation of production flow using Matlab system.* [in:] Lipski J., Świć A., *Optimization of production processes,* Wyd. Politechniki Lubelskiej, Lublin, 2013, p. 64–74.

[4] HAVLÍK, ŠTEFAN-HRICKO, JAROSLAV: *The analysis and design study of high speed robotic devices.* In Applied mechanics and materials, 2013, vol. 282, p. 18–26.

[5] MIKOLAJCZYK T. et al.: *Multipurpose Mobile Robot*. Applied Mechanics and Materials, vol. 282, (2013), p. 152–157.

[6] MIKOLAJCZYK T., OLARU A., KRAINSKI P.: *Adaptive control system for drill machine*. In: Applied Mechanics and Materials, vol. 436 (2013) p. 445–450.

[7] PIOTROWSKI A.: *The Spectacle of Architectural Discourses,* at Architectural Theory Review, (13:2, Routledge, 2008), p. 130–144.

[8] SLAMKA J. et al.: *Automatic manipulation of parts made from yielding material*. In: Applied Mechanics and Materials, vol. 332 (2013), p. 432–430.

[9] ŚWIĆ A., WOŁOS D., ZUBRZYCKI J., OPIELAK M., GOLA A., TARANENKO V.: *Accuracy Control in the Machining of Low Rigidity Shafts.* Applied Mechanics and Materials, Vol. 613, 2014, p. 357–367.

Jozef Varga[1], *Ján Semjon*[2]

SECOND VERSION OF MECHANISM FOR SOLVING RUBIK'S CUBE

1. INTRODUCTION

This contribution described construction and scanning process of second version of solver with 2 lower grippers and two upper grippers, resulting in approximately two minutes for single cube solution [5,8]. In this solution was include statistical analysis of Thistlethwait's 45 algorithm required for solving process optimazation. Mechanical design, electronics, system overview, performance and limitations of upgraded 4 gripper version are explained in detail as well.

2. MECHANICAL CONSTRUCTION

As mentioned in the beginning, our motivation was to by develop fully pneumatical Rubik's cube solver to demonstrate possibilities of pneumatical approach in precise manipulation tasks. 3D CAD design shown in figure 1 gives an overview of whole construction [1,3,4,10].

Supporting frame is assembled of aluminum mounting profiles 30x30mm and attached to wooden base providing cover for electronic part of a system. Four manipulation units consist of three air modules – compact guide cylinder, rotary table and a gripper module. For our particular construction, SMC modules were used, since they provided best price/performance ratio [2,9].

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotic, Letna 9, 04200, Košice, Slovakia, e-mail: jozef.varga.2@tuke.sk
[2] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotic, Letna 9, 04200, Košice, Slovakia, e-mail: jan.semjon@tuke.sk

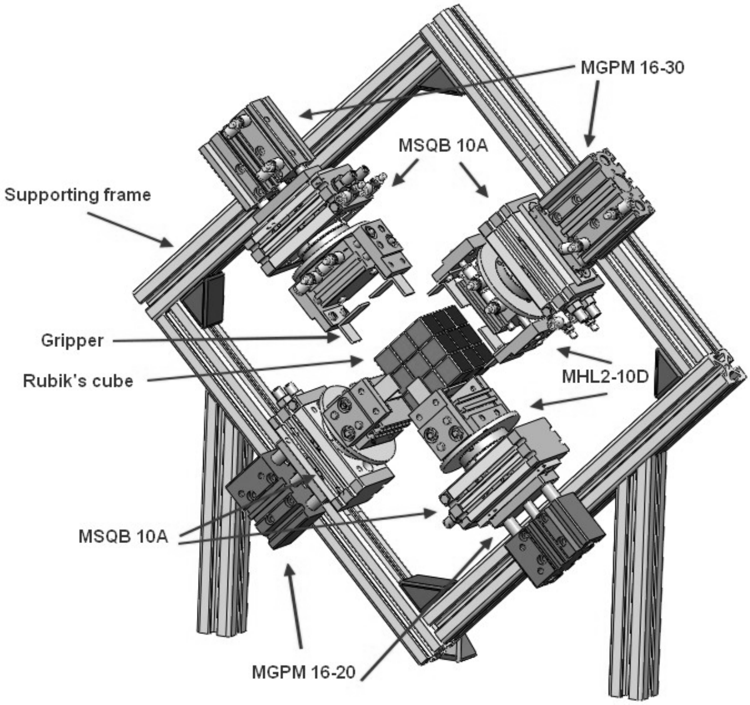


Fig. 1. Mechanical design of Rubik's cube solver [source: own study]

The first component that needed to be selected in Rubik's solver mechanical design was gripper unit. SMC provides several types of components including angle, parallel or three point grippers [6,7]. Considering all possible options, MHL parallel units were selected as best suitable for our task. MHL in general are double piston parallel style grippers with large holding force, which are available in several sizes.

In order to select particular type of MHL gripper module, it was necessary to compute holding force and determine holding point distance. If Rubik's cube weight is m_{rc} = 0,12 kg , safety factor k = 10, then required holding force is computed as follows:

$$F_u = m_{rk} \times g \times k = 11{,}8N \tag{1}$$

Considering holding force F_u, distance from grasping point R = 30 mm and Rubik's cube width L = 57 mm, MHL2-10D unit, providing opening/closing stroke range 56–76 mm was selected. As shown in diagram in Fig. 2 required holding force can be achieved already at 0.4 MPa.

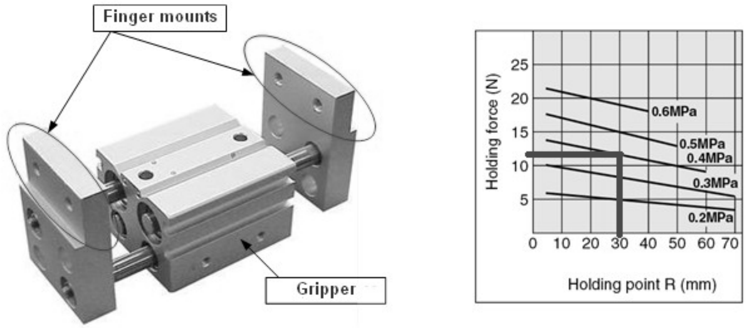


Fig. 2. MHL2-10D gripper unit and appropriate holding force graph [source: own study]

Rotation of gripper unit is SMC MSQ units. MSQ is compact rotary table including load bearings, mounting face, with a rack-and-pinion style rotary acutator. Achievable rotating range of MSQ tables is 190 degrees, in case of Rubik's cube manipulation; adjustments are set to 0-90°. In order to select optimal rotary table type, two important variables - moment of inertia and time of 90° rotation must be determined.

Considering weight of Rubik's cube m_{rc} = 0,12 kg , weight of gripper unit m_{GU} = 0,28 kg as well as dimensions of gripper unit, moment of inertia can be computed as follows:

$$I = (m_{rc} + m_{GU}) \times \frac{a^2 + b^2}{12} = 1{,}51 \times 10^{-4}\, kgm^2 \tag{2}$$

If duration of 90 degree rotation is set to 0.3s, MSQB-10A unit meets computed requirements as shown in diagram in Fig. 3.

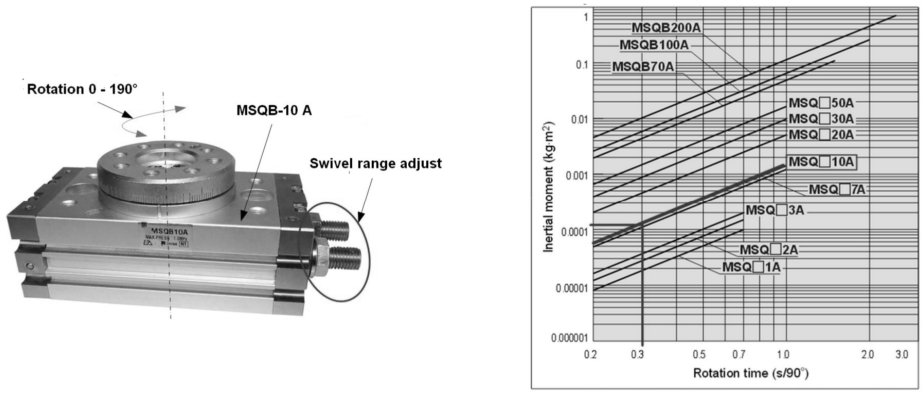


Fig. 3. MSQB-10A unit and appropriate rotation time – inertial moment selection graph [source: own study]

As mentioned above, current mechanism allows manipulating with four sides of cube directly. But solving process require clockwise and counterclockwise manipulation with all six sides of the cube, therefore it is necessary to turn the cube every time the front or back side of the cube needs to be rotated. However, turning the cube without stroking of particular units is not possible because of mutual gripper collisions. Application of compact guide cylinders eliminates this problem, by providing stroking capability for each manipulation unit. When rotating the cube, only gripper holding the cube can be ejected, remaining three must be shut to avoid collision. From all available cylinder units, MGPM class was most suitable for our construction mainly because of its flat design and rectangular mount allowing simple attachment of rotary unit.

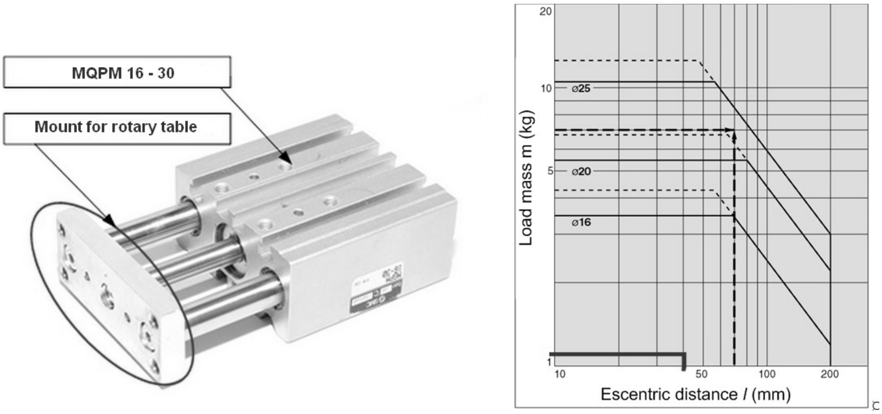


Fig. 4. MPQM 16-30 and appropriate load mass – eccentric distance selection graph [source: own study]

MGPM in general is compact guide cylinder designed for high side load applications with available strokes within range 20 – 400 mm. Since MGPM load of single unit in our case was approximately 1kg, model size with cylinder diameter D=16 mm according to graph in Fig. 4 was selected. Lower two gripper units are equipped by 20 mm stroke, while upper grippers units use 30 mm strokes. This configuration in combination with dimensions of supporting frame results in appropriate gripper position with respect to the cube.

Comparison of prior and current version of Rubik's solver is shown in Fig. 5.

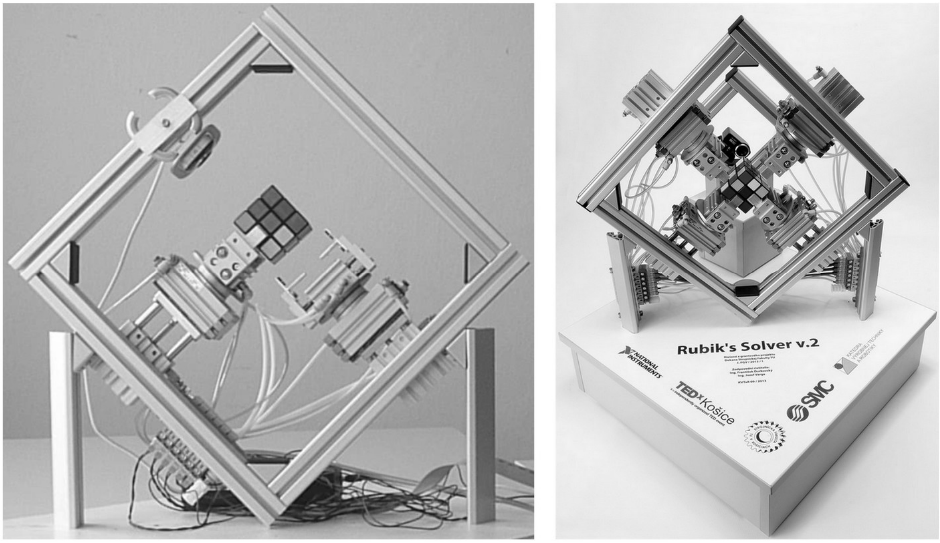


Fig. 5. Comparison of previous and current solver version [source: own study]

3. RUBIK CUBE SCANNING PROCESS

Randomly mixed cube is inserted into solver under angle of 45° degree and grasped by two lower grippers. Initial orientation of inserted cube is explicitly defined – blue center facing visitor, yellow center in top left side and red center in top right side. Solver is programmed to turn the cube to face each side to camera sequentially, while the initial orientation provides following order of scanned sides – red, blue, orange, green, white yellow. Snapshot of each side is taken by webcam and stored into the workspace. Example output of scanning process is shown in Fig. 6.

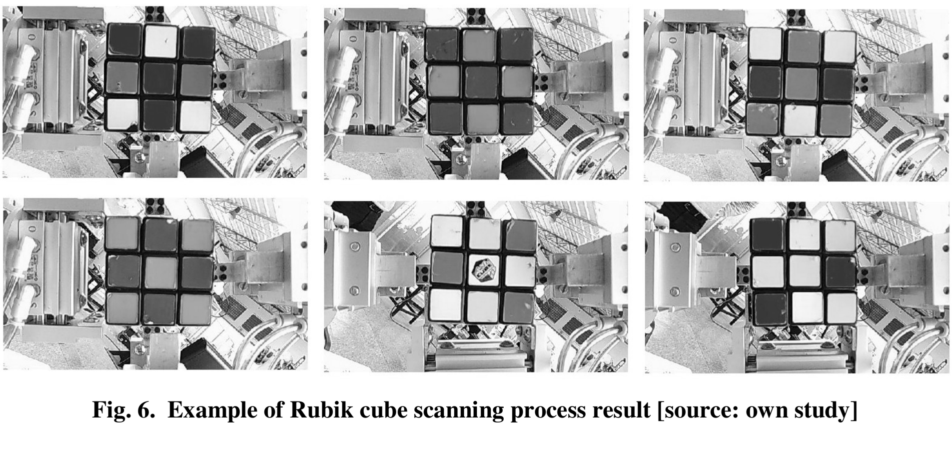


Fig. 6. Example of Rubik cube scanning process result [source: own study]

Cube scanning process was optimized for minimal number of moves required to turn every single cube side to the camera. It is also the reason why results of scan do not match the real cube state shown in Fig. 7 exactly - red and orange side are 90 degrees counterclockwise rotated while white side is rotated 180 degrees with respect to real state. In fact 90 degree orientation is applied to blue and green side as well; it is just not visible due to symmetric side. Only yellow side scan remains the same.

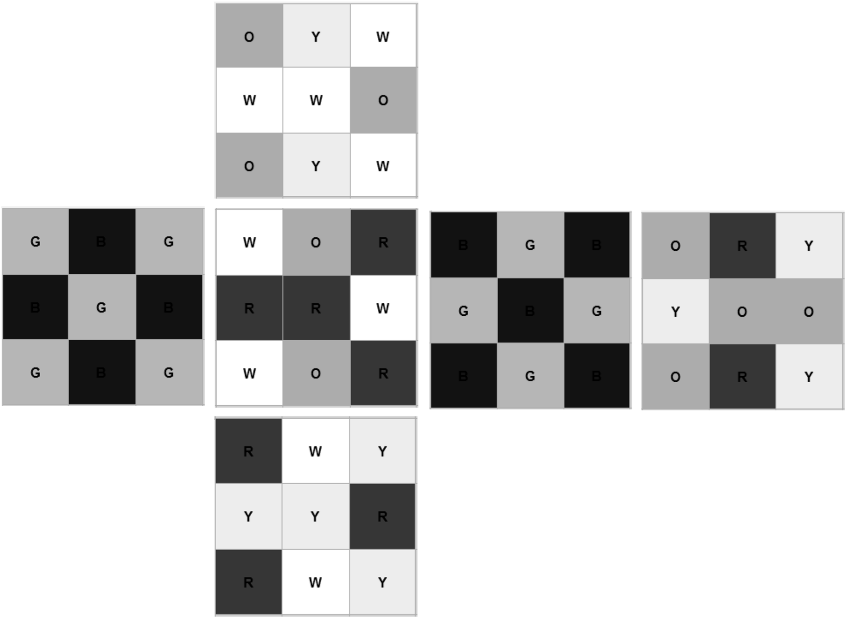


Fig. 7. The real state of example cube [source: own study]

Rubik's cube is mathematically represented as 3x3x6 matrix, where numbers 1-6 are assigned to particular colors: 1 – red, 2 – blue, 3 – orange, 4 – green, 5 – white, 6 – yellow. Our goal is to provide an algorithm which generates matrix R, if given snapshots of six cube sides. Mathematical representation of example cube shown in Fig. 3 is following:

$$R(:,:,1) = \begin{bmatrix} 5 & 3 & 1 \\ 1 & 1 & 5 \\ 5 & 3 & 1 \end{bmatrix} \quad R(:,:,2) = \begin{bmatrix} 2 & 4 & 2 \\ 4 & 2 & 4 \\ 2 & 4 & 2 \end{bmatrix} \quad R(:,:,3) = \begin{bmatrix} 3 & 1 & 6 \\ 6 & 3 & 3 \\ 3 & 1 & 6 \end{bmatrix}$$

$$R(:,:,4)=\begin{bmatrix}4&2&4\\2&4&2\\4&2&4\end{bmatrix}\quad R(:,:,5)=\begin{bmatrix}3&6&5\\5&5&3\\3&6&5\end{bmatrix}\quad R(:,:,6)=\begin{bmatrix}1&5&6\\6&6&1\\1&5&6\end{bmatrix}$$

4. CONCLUSIONS

Construction of Rubik's solver can provide a lot of useful experience, especially when studying mechatronics, since it requires combining several different subsystems into one functional mechanism. Our main motivation was to build Rubik's cube solver using standard industrial components to demonstrate pneumatical approach for solving precise manipulation tasks. First version has proven the basic functionality, adding 2 more grippers in second version have reduced average solving time under 2 minutes.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multirobotic systems", supported by the Research & Development operational Program funded by the ERDF.

REFERENCES

[1] BENIAK, JURAJ-KRIŽAN, PETER-MATÚŠ, MILOŠ: *Accuracy of Rapid Prototyped models with using of FDM technology.* Applied Mechanics and Materials, vol. 613, p. 390–395.

[2] BENIAK, JURAJ-KRIŽAN, PETER-MATÚŠ, MILOŠ-KOVÁČOVÁ, MONIKA: *The operating load of a disintegration machine.* Acta Polytechnicam, vol. 54, no. 1 (2014), p. 1–5.

[3] ČIRIP M., HAJDUK M.: *Návrh stabilizácie a matematických modelov kráčania humanoidných robotov: písomná práca k dizertačnej skúške*, Košice, 2010, p. 47.

[4] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View.* [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[5] HAJDUK M., MARKO Ľ.: *Prístupy k navrhovaniu a riadenia exoskelotonu.* Písomná práca k dizertačnej skúške, Košice, 2010, p. 47.

[6] JONG HWAN KIM, PRAHLAD V.: *Trends in Intelligent robotics.* 13^{th} FIRA Robot World Congress, FIRA 2010 Bangalore, India, September 15–17, 2010 Proceedings, Springer Berlin Heidelberg New York, 2010.

[7] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A.: *A predictive model of multi-stage production planning.* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[8] NEMEC M.: *Návrh bipedálneho kráčajúceho podvozku servisného robota*, doktorandská dizertačná práca, KVTaR, SjF TUKE, Košice 2005.

[9] OLARU A.: *Virtual LabVIEW instrumentation in the technical research of the robots elements and the systéme,* Bren P Publishing, Bucharest 2002.

[10] RISTIC D: *RoboWalker Mobile Robot – Assisted Gait Rehabilitation System*, Durrant 2010.

Rudolf Jánoš[1], *Lucia Koukolová*[2]

METHODOLOGY OF PRELIMINARY CALCULATIONS OF ROBOTS WITH PARALLEL STRUCTURE

1. INTRODUCTION

The mechanisms with a parallel kinematic structure (Hexapod, 3-pods), having three to six parallel members (arms) that are connected between the base and the platform, respectively output member [7]. Parallel mechanisms generally comprise two platforms, one of which is controlled by length variable arms, working in parallel [1,4]. The output member is defined as a movable platform, which is three to six degrees of freedom to the other platform – the base. It can vary individually in each of the three linear and three angular directions or in any combination. The resulting movement of the platform is the current movement and control of arms [3,5].

The workspace of the robot with parallel kinematic structure is not fixed and it needs to be calculated. It must be taken of the length of each joint and rotation of each joint.

2. HANDLING CHARACTERISTICS OF PARALLEL ROBOTS

Workspace industrial robot can be defined as the set of all end-effector positions of the robot arm, which can be achieved in the end positions of the individual axes of the robot [2,6]. Specifies the volume of the space to the maximum reach to the robot flange respectively. Effector that is attached to the flange of the robot (gripper, tool, etc.).

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotics, Nemcovej 32, 042 00 Kosice, Slovak Republic,
e-mail: rudolf.janos@tuke.sk

[2] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotics, Nemcovej 32, 042 00 Kosice, Slovak Republic,
e-mail: lucia.koukolova@tuke.sk

The border positions workspace of the robot is not usually possible any orientation of the end effector. As a rule, difficult access effector of the manipulated object, which is in such a marginal position workspace.

Evaluation criteria are based on definitions:

Workspace (W) – reachable workspace, is set of points which is capable of a reference point of the robot mechanism achieved, irrespective of the orientation of the end members.

Passive space V (A) – space is interesting structure of the robot when moving the reference point to the border of the work area. Criteria for evaluation of the responsibility of an industrial robot can be defined as follows.

Operating indicator PU – in terms of operational use are also effective geometrical arrangement of the mechanism of the robot, which is able to cover a large work area with minimal passive space, ie, PU is close to 1:

$$PU = \frac{V(W)}{V(A)} \qquad 0 \le PU \le 1 \tag{1}$$

Volume index OI – is relatively "amount" of structures mechanisms required to generate a given amount of working space is the proportion of the working area and the total length of the shoulder mechanism of the robot R, where NOI is the standard volume index:

$$OI = \frac{V(W)}{R^2} \qquad 0 \le OI \le NOI \tag{2}$$

where in R is the sum of the length of the arms of the rated mechanism:

$$R = \sum d_i \qquad i = 1,2,..., N \tag{3}$$

The maximum volume V (W) max for planar parallel mechanism is the volume of a circle of radius R centered on the mechanism

$$V(W) = \pi \cdot R^2 \qquad NOI = \frac{\pi \cdot R^2}{R^2} = \pi \tag{4}$$

NOI should be used as the legitimate factor to create a range of assessment $0 \le OI \le NOI$.

Efficient geometry parallel mechanism is characterized by the value of OI near NOI volume fraction OP – is relatively reconciliation volume achievable workspace of a parallel mechanism and serial shoulders, forming the branch, is the proportion of the volume achievable workspace and maximum volume of space that covers the j-th separate arm.

$$OP_j = \frac{V(W)}{V_j} \qquad 0 \leq OP_j \leq 1 \tag{5}$$

The value of the volume fraction characterized by "participation" of individual arms to the workspace of the mechanism. Size of the working space is limited parallel link.

Index maneuverability IM – is the ability to reach any orientation mechanism output member, the reference point is in the position defined in the primary workspace and the achievable workspace:

$$IM = \frac{V(W_P)}{V(W)} \qquad 0 \leq IM \leq 1 \tag{6}$$

The primary work space; means such a set of points where the point of identifying the mechanism of the reference point of the random point of the group, is made possible rotation of the output member through 360° about an axis passing through this point and perpendicular to the planes of the system in which the members of the moving mechanism. Good alignment mechanism is characterized by a value IM close to 1.

3. THE PROBLEM OF SINGULARITY

Singularity - a condition caused by collinear (geometrically related, lying on one line) clearance of two or more robot axes resulting from unanticipated movements of the robot (EN ISO 10218-1) – indicates the reasons (passivity, redundancy, total binding, irregularity, ...) which make the actual mobility nS mechanism differs from the theoretical mobility n, t, j. nS ≠ n – is related to the static behavior of the parallel mechanism (coupled mechanical system VMS is in immediate singular state, where its members can move the dimensionless value position coordinates member, VMS is in a permanent state of singular if its members can move on final value of the position coordinates member; VMS – assembly members (bodies), the relative movement limiting geometric relationships/connections) – let F the load imposed on the work platform robot and τ vector forces bullion – variables are linearly dependent:

$$F = J^{-T}(X)\tau \tag{7}$$

Where J^{-T} is transposed Jacobian inverse of the robot, is indicative of the location. Each of the forces in the joints can be calculated, where in A determinant of the submatrix corresponding to the τ_i.

$$\tau_i = \frac{A}{|J^{-T}|} \tag{8}$$

Provided that A is different from zero, forces bullion grow beyond all bounds in every position called singular location where the determinant J^{-T} is zero, causing the collapse of the movement of the robot (the collapse is already before the singular position).

Although the condition $|J^{-T}| = 0$ may seem like a simple condition as matrix J^{-T} the analytical form, complete the calculation of the determinant leads to complex mathematical relationships with a large number of parameters (especially if the device has 6 DOF), which is in practice unusable.

The singular position is present in special geometric configuration, VMS, and they can be determined for any number of DOF of the Use of bar geometry. Are there efficient algorithms that allow to detect the presence of singularities in either the achievable workspace of the robot, or in a specific workspace platform. It also can be virtually real-time test for the presence of singularities on any trajectory, however, a need for better characterization of singular configurations - singularity are dangerous only if the denominator is zero only τ_i – In fact, if the numerator is zero, forces bullion may still end, the usual view that singularities is necessary to avoid: this is not the handlers that are permanently singular – permanently singular robots may be of interest, allow to perform complex movements of a robot platform only movement one drive (assuming that the variability of the singular dimension 1, points such movements for machining operations.

4. CONCLUSIONS

These problems singularities of parallel kinematics can be solved by using redundant (surplus) drives – number of arms to drive is more than a platform of degrees of freedom – do not occur singular position, substantially increasing stiffness and dynamics, increases the kinematic accuracy, opens the possibility of on-line self-calibration.

Acknowledgements

Paper is the result of the project implementation: VEGA-1/0810/11" Principles of profiling and cooperation multi-robotic systems".

REFERENCES

[1] GOLA A., ŚWIĆ A., *Intelligent decision support system for FMS machine tool subsystem design.* Applied Computer Science, vol. 3, no. 1, 2007, p. 109–124.

[2] JANTAPREMJIT P., AUSTIN D.: *Design of a modular Self-Reconfigurable Robot.* Cannbera 2005.

[3] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning.* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[4] MERLET J. P.: *Parallel robots. Second Edition.* Springer, 2006, p. 327.

[5] SOBASZEK Ł, GOLA A., ŚWIĆ A.: *Creating Robust Schedules Based on Previous Production Processes.* Actual Problems of Economics, no. 8 (158) 2014, p. 488–495.

[6] ŚWIĆ A., GOLA A.: *A Method of Qualification of Parts for Production in a Flexible Manufacturing System.* Actual Problems of Economics, no. 11 (149) 2013, p. 576–585.

[7] TLUSTÝ J. et al.: *Fundamental Comparison of the Use of Serial and Parallel Kinematics for Machines Tools.* Annals of the ClRP, vol. 48, no. 7, 1999, p.351–356.

Jarosław Zubrzycki[1], *Antoni Świć*[1]

AUTOMATION OF SHAFTS MACHINING

1. INTRODUCTION

Methods of building mathematical model (MM) of the control object significantly depends on the capacity of apriorical information available from the moment of starting investigating of the given object. Task of developing a model can be realized in two stages. In the first stage, basing on this apriorical information regarding physical processes occurring in technological process, structure of the object is developed. Usually, this model includes unknown parameters, which are hard or impossible to be found basing on apriorical data. Initial structural model can contain certain elements that are not necessary in next stages of MM development. During second stage, basing on the experimental tests, unknown parameters are defined and model structure is improved. In many cases it is possible to simplify initial model structure. Dynamic system (UD) of the machining process is a Technological system (UT) – OUPN i.e. machine tool with realized technolo-gical process (UT) of the turning processing.

2. IDENTIFICATION OF DYNAMIC SYSTEM OF CUTTING PROCESSING FOR SHAFTS WITH CONTROL REALIZED USING LONGITUDINAL FEED

Basic goal of developing model of turning process in designing control system is minimization of measurement-shape errors of the machined tools. Taking into account the fact, that main cause of these errors in case of longitudinal turning is elastic deformation of the technological system and due to functional dependence of cutting force, these parameters are to be considered as input values of controlling object (OS).

[1] Lublin University of Technology, Institute of Technological Systems of Information, Nadbystrzycka Str. 36, 20-618, Lublin, Poland

Turning process is nonlinear. However, due to assumed use of the model to control and, in particular, to realize a task of stabilizing cutting forces in time (where output variables change slightly) one can linearize nonlinear dependencies near statistic point of operation.

Basing on the analysis of cutting layer geometry, cutting forces, elastic properties, technological system and process of forming section area of cut surface with taking into account phenomenon of cutting "along trace", a system of dependencies in an operator form describing dynamic features of the machining process is obtained (Fig. 1) [1,2].

In turning process influence of machining traces on the process course is characteristic – it is so called cutting "along trace". It occurs since the parameters of cut metal layer in a moment *t* are determined both by instantaneous position of the edge and both by its coordinates in a moment of previous rotation of parts t-τ, i.e. in a moment delayed by time of one rotation.

Denotation of variables on the structural diagram are: s – Laplace transformation operator, F_f – feeding component of cutting force, F_c – main component, F_r – radial component, n_{cz} – rotational speed of the speed part, v_r – speed of longitudinal feed, c_1 – material hardness, b_1 – processing allowance, $\tau=l/n_{cz}$ – delay.

Relations between value of elastic deformation and components of cutting forces in the operator form are described with linearized dependencies:

$$\Delta g_i(s) = \Delta H_i(s)\Delta H_i(s), i = \{x, y, z\} \tag{1}$$

After taking into account that time constants of chip formation for different components of cutting forces do not differ much, we can assume:

$$M_x(s)N_x(s) = M_y(s)N_y(s) \tag{2}$$

Using above dependency, a function of object transition (after transformations) can be written for i-th component of cutting force in a following form:

$$G_{v_f F_i}(s) = \frac{M_i(s)G_\tau(s)}{s[1 + N_y(s)H_{yy}(s) + G_\tau(s)[M_x(s)H_{xx}(s) + K_K M_y(s)H_{yy}(s)]]} \tag{3}$$

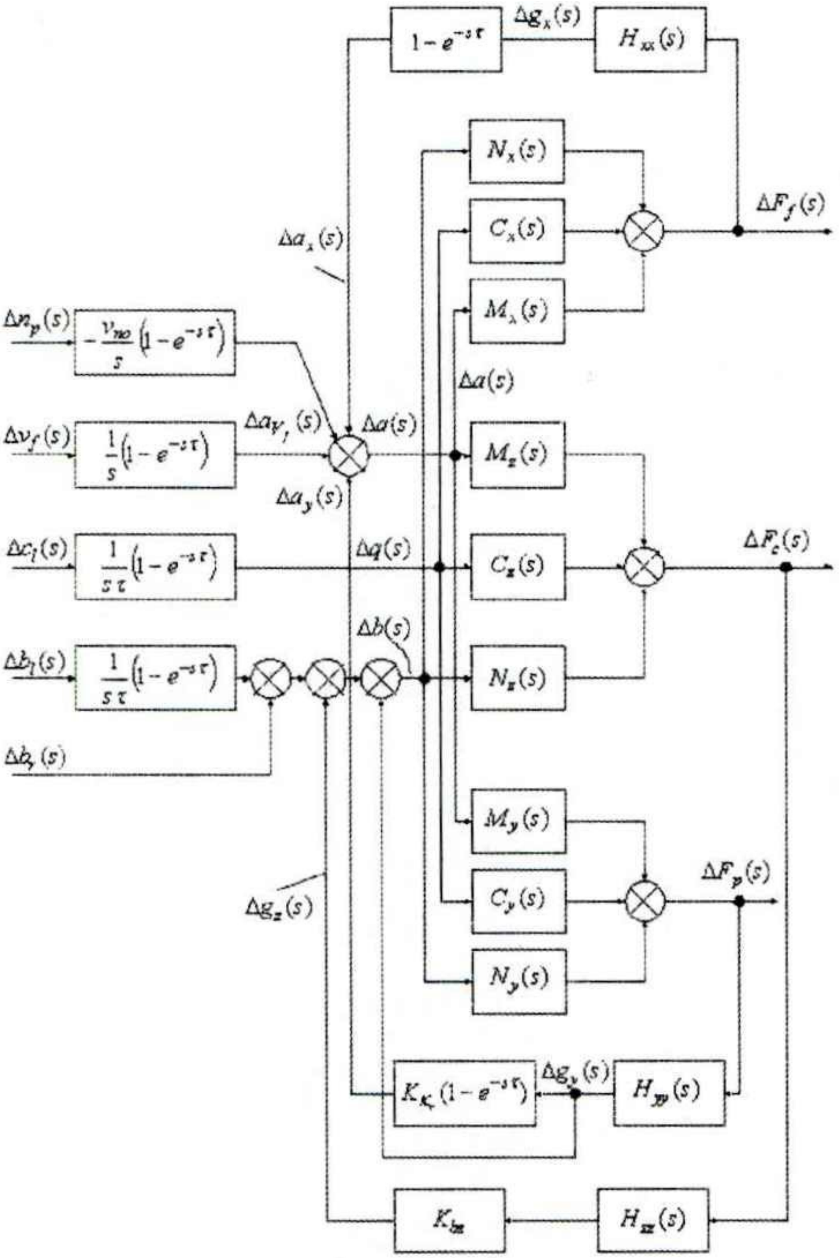


Fig. 1. Output structural diagram of the control object [source: own study]

Assuming transition function of chip forming process in a form of non-periodic element with time constant T_c and assuming oscillating secondary element with constant T_{us} and attenuation coefficient ξ as a model of dynamic properties of control system we get:

$$G_{v_f g_i}(s) = \frac{m_x(s)G_\tau(s)}{s[(T_c s+1)(T_{us}s^2+2\xi T_{us}s+1)+B_1 G_\tau(s)+n_y h_{yy}]} \tag{4}$$

or, after taking into account (1):

$$G_{v_f g_i}(s) = \frac{m_x h_{xx}(s)G_\tau(s)}{s[(T_c s+1)(T_{us}^2 s^2+2\xi T_{us}s+1)+B_1 G_\tau(s)+n_y h_{yy}]} \tag{5}$$

Due to the above, forming process of cut layer section is significantly affected by cutting “along trace” and by elastic deformation of the technological system. Process of forming section of cut layer can be described by a system of integral-differential equations with delayed argument. The variables characterizing section of cut layer depend on input variables and elastic deformations of the technological system.

3. OUTPUT MATHEMATICAL MODEL

Controlling activity, in a form of longitudinal feed, is used in the most effective way to optimize the processes of machining the parts with relatively high rigidity. Preliminary analysis shows that in this case one can take into account only own susceptibilities of the elements of technological system.

According to the set of equations [1] and equations (2-4) the output diagram of the structure of control object can be presented in a form like in Fig. 1. It shows that current value of thickness of the section and its increment are determined by three components:

$$\Delta a(s) = \Delta a_{v_f}(s) - \Delta a_x(s) - \Delta a_y(s)$$

where: Δa_{v_f} – a component that depends on the speed of longitudinal feed width of the section of cut layer without taking into account elastic deformations), Δa_x and Δa_y – components conditioned by elastic deformations for X and Y coordinates.

Increment of a current value of section width depends on elastic deformations of the technological system for Y and Z coordinates.

In that way, in case of the considered MM it is characterized by the presence of internal closed circuits in its structure – they are conditioned by an influence of the elastic deformations on the elements of the section of cut layer and singularities of cutting "along trace".

In the further analysis influence of elastic deformations for Z coordinate on the width of a section as insignificant. Considered structure can be transformed assuming speed of longitudinal feed as input value. Resulting form is shown in Fig. 2.

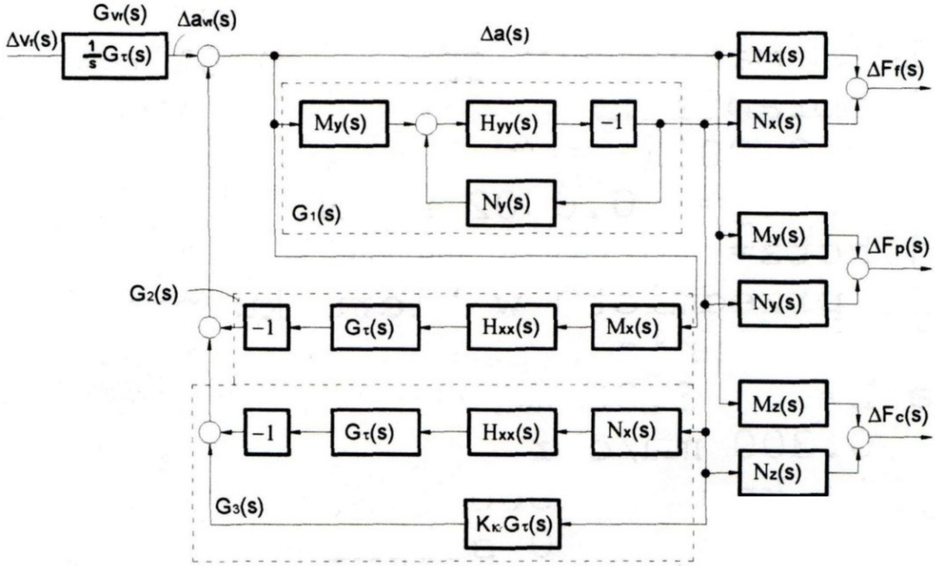


Fig. 2. Structural diagram of the control object [source: own study]

Equivalent transition functions marked in Fig. 2 as $G_1(s)$, $G_2(s)$, $G_3(s)$ are equal to:

$$G_1(s) = -M_y(s)\frac{H_{yy}(s)}{1+N_y(s)H_{yy}(s)} \tag{6}$$

$$G_2(s) = -G_\tau(s)M_x(s)H_{xx}(s) \tag{7}$$

$$G_3(s) = G_\tau(s)[K_{\kappa_r} - N_x(s)H_{xx}(s) \tag{8}$$

Transition function for the components of cutting forces, e.g. F_f:

$$G_{v_f F_x}(s) = \frac{\Delta F_f(s)}{\Delta v_f(s)} = \frac{G_\tau(s)[M_x(x) + G_1(s) N_x(s)]}{s[1 - G_{sz}(s)]} \tag{9}$$

The following diagram of indices has been assumed for (here and later) denoting coefficients of gain and transition functions. First letter index indicate input coefficient (in the given case v_f), second – output value (F – cutting force, *g* – elastic deformation), third (if necessary) shows component of a cutting force or elastic deformation *i={x,y,z}*. Transforming dependency for $G_{Vf}g,(s)$. and applying the last expression for its denominator, we obtain:

$$G_{v_f g_i}(s) = \frac{m_x h_{xx} G_\tau(s)}{s[(T_c s + 1)(T_{us}^2 s^2 + 2\xi T_{us} s + 1) + B_1 G_\tau(s) + n_y h_{yy}]} \tag{10}$$

$$\text{where } B_1 = m_x h_x + K_{\kappa_r} m_y h_y \tag{11}$$

4. ANALYSIS OF THE POSSIBILITIES OF SIMPLIFYING MATHEMATICAL MODELS

An analysis of the obtained dependencies of transition function of the control object has been performed for their simplification. Mathematical model of the control object in a form of transition function (10) takes into account inertia of the chip formation process and elastic system together with delay caused by singularities of cutting “along trace”. Characteristic singularity of the mathematical model is presence of internal, closed circuit in its structure. Thus, it is important to investigate features of the closed circuit and analyze its stability.

Stability of the mentioned circuit is determined by so called “vibrostability” of the machine [3]. If the stability conditions are not met, during cutting in dynamic system self-excited vibrations occur. While developing mathematical model of the dynamic machines system it was assumed that “vibrostability” of the machines is ensured i.e. closed circuit is stable.

Relation between time constants of the elastic system T_{us}, chip formation process *T,* and delay time τ were investigated. Delay τ, inversely proportional to the rotational speed of a part is not less than 0,1 to 0,2s in case of lathes. For medium size machine tools rotational speed of a spindle is 2000 rpm, thus minimum τ value is 0,03 s. Own resonance frequencies of equivalent elastic system of a machine tool and of a part for medium size lathes are within a range of frequencies higher than 50 Hz, i.e. the largest equivalent time constant T_{us} does not exceed 0,003s. Computations of the time constant of chip formation show that in ordinary cutting conditions values of T do not exceed 0,005 to 0,001s hence delay τ in (10), contained in a transition function $G\tau(s)$, exhibits the largest value and exceeds (by an order of magnitude) time constants T_{uc} and T_c [1,2]. Properties of equivalent closed circuit (if its stability conditions are met) are determined mainly by an element with the highest inertia – in this case an element with transition function:

$$G_\tau(s) = 1 - e^{-s\tau}$$

In later part a possibility of neglecting "small" time constants regarding transition function of the investigated object was evaluated. In order to verify formed errors frequency domain was used – frequency characteristics.

Frequency characteristics of a model are obtained by substituting in (10) $s = j\omega$ and by using Euler's formulas for exponential function:

$$e^{-j\omega\tau} = \cos\omega\tau - j\sin\omega\tau$$

After transformation of a dependency for amplitude characteristics (ACH) and phase characteristics (FCH) one can write:

$$A(\omega) = m_i h_{ij} \frac{\left|2\sin(\frac{\omega\tau}{2})\right|}{\omega\sqrt{C_1^2 + D_1^2}} \cdot \varphi(\omega) = -\frac{\omega\tau}{2} - arctg\left(\frac{D_1}{C_1}\right) \qquad (12)$$

where:

$$C_1 = 1 + n_y h_{yy} + B_1 - B_1\cos\omega\tau - (T_{us}^2 + 2\xi T_{us}T_c)\omega^2$$

$$D_1 = B_1\sin\omega\tau - (T_c + 2\xi T_{us})\omega - T_{us}^2 T_c\omega^3$$

Fig. 3 shows functions of frequency characteristics (dashed lines) $A_1(\omega)$, $L_1(\omega)$ and $\varphi_1(\omega)$ of the mathematical model of output transition function (9) that were obtained from numerical calculations for the following data: $m_i n_i = 1$, $\tau = 1$, $B_1 = 0,6$, $T_{us}/\tau = 0,1$, $T_c/\tau = 0,05$.

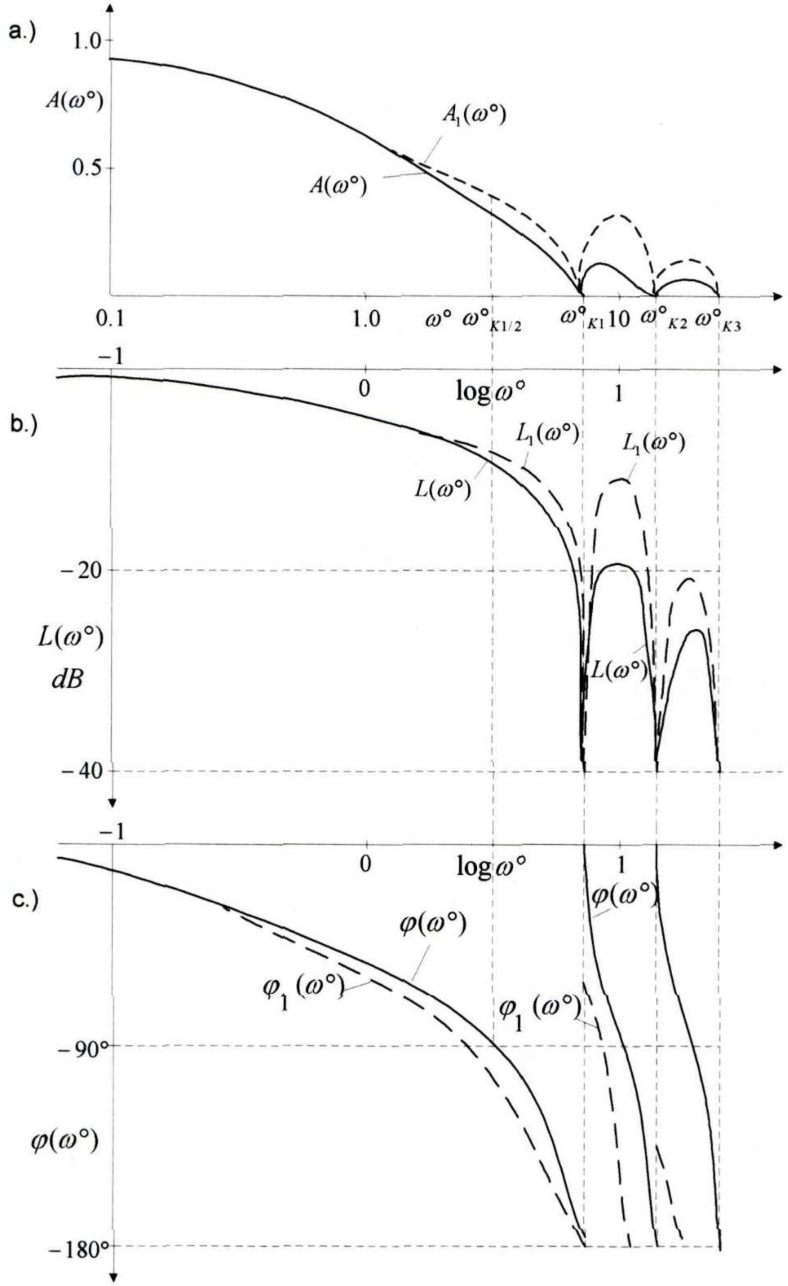


Fig. 3. Frequency characteristics of mathematical model of a dynamic system [source: own study]

Thanks to assumed unit values $m_i n_i$ and τ, presented relations can be considered as generalized characteristics of the mathematical model in relative units. Their form does not depend on the particular values of the time constants but their ratio and coefficient B_1. An argument in frequency characteristics is relative frequency $\omega^o = \omega / \omega_b$, where value $\omega_b = 1/\tau$ [1] is assumed as base frequency. Full lines in Fig. 3 show characteristics of a simplified model $A(\omega^o), \varphi(\omega^o), L(\omega^o)$, obtained by neglecting time constants of the elastic model and chip formation processes: $T_{us}=T_c=0$.

Analysis of the obtained relations show that output and approximated ACH and FCH are periodical functions of frequency. For the critical values of frequency $\omega_k^o = 2\pi k / \tau$ (k=1,2,3,…….), amplitude characteristics assumes zero values and the coordinates of logarithmic amplitude characteristics $L(\omega_k) \Rightarrow -\infty$. Phase shift reaches -180.

Reduction of the object equivalent gain coefficient to zero for the critical frequencies is explained by singularities of cutting "along trace". In case of critical frequencies trajectory of blade motion on developed surface for current rotation remains equally distant to the trajectory of motion in previous rotation. Consequently, increment of section thickness, cutting forces and elastic deformations equals zero.

For frequencies higher than first critical $\omega_k^o = 2\pi k$ maximum value of $A(\omega^o)$ does not exceed (0,08 to 0,18)A(0) with changing B_1 coefficient in a range 0,1 to 1. Logarithmic phase characteristic is a discontinuous, periodic function. Points of their discontinuity overlaps with critical values of the frequency. Values of the logarithmic phase characteristics of an approximated model change within a range from 0 to -□. Taking into account inertia of the chip formation process and elastic system leads to changing value of logarithmic amplitude characteristics and phase characteristics. Moreover, it leads to additional phase shifts value and to the first critical frequency the difference between output and approximated logarithmic phase characteristics does not exceed 3 to 4dB. In this range of frequencies deviation of approximated $\varphi(\omega^o)$ phase characteristics from output $\varphi_1(\omega^o)$ occurs only near critical frequency value. Within the range of frequencies higher than critical one deviation between phase characteristics is significant.

During synthesis of the corrective elements of the automatic control system the cut-off frequency is chosen on the left side of the first critical frequency of mathematical model of control object. It allows to consider frequency characteristics of the mathematical model limiting frequency range to smaller ones than first critical equal to $2\pi/\tau$. For the given frequency range, as performed analysis showed, inertia of the chip formation process and elastic deformation can be neglected without significant error and assume at the end:

$$H_{ii}(s) = h_{ii}, M_i(s) = m_i, N_i(s) = n_i, C_i(s) = c_i, \tag{13}$$

Then, the approximated dependencies of the object transition function for recognized control activity and for the output values in a form cutting forces and elastic deformations are as follows:

$$G_{v_f F_i}(s) = \frac{\Delta F_i(s)}{\Delta v_f(s)} = \frac{K_{1v_f F_i} G_\tau(s)}{s(1+BG_\tau(s))} \tag{14}$$

$$G_{v_f g_i}(s) = \frac{\Delta g_i(s)}{\Delta v_f(s)} = \frac{K_{1v_f g_i} G_\tau(s)}{s(1+BG_\tau(s))} \tag{15}$$

where:

$$K_{1v_f F_i} = m_i \left[1 - \frac{m_y h_{yy} n_i}{(1+n_y h_{yy}) m_i} \right], K_{1v_f g_i} = K_{1v_f Fi} h_{ii} \tag{16}$$

$$B = \frac{m_x h_{xx} + m_y h_{yy} K_{\kappa_r}}{1 + n_y h_{yy}} \tag{17}$$

In this way, while developing mathematical models for control over dynamic system of machine tools with met condition of “vibrostability” it is allowed to describe the properties of the elastic system and chip formation process with gain coefficient. It means that mentioned elements can be considered as proportional.

One has to note that dependency between output coordinates (components of the cutting force and elastic deformations) and intermediate coordinate – thickness of a cut layer Δa_{v_f} as an input is presented by transition function of the closed circuit:

$$G_{zkF}(s) = \frac{\Delta F_i(s)}{\Delta a_{vf}(s)} = \frac{m_i}{1+n_y h_{yy}} \cdot \frac{1}{[1+BG_\tau(s)]} \tag{18}$$

$$G_{zkg}(s) = \frac{\Delta g_i(s)}{\Delta a_{vf}(s)} = \frac{m_i h_i}{1+n_y h_{yy}} \cdot \frac{1}{[1+BG_\tau(s)]} \tag{19}$$

In rough processing, when values of B coefficient are larger than 0,1, in order to obtain simplified relations one has to use development of the exponential function into Pade series. Limitation to the first two components of the Pade series one obtains:

$$
\begin{aligned}
&G_{v_f F_i}(s) = \frac{\Delta F_i(s)}{\Delta v_f(s)} = \frac{K_{v_f F_i}}{(T_{o1}s+1)(T_{o2}s+1)}, \\
&T_{o1,o2} = 0{,}5\tau\left[0{,}5 + B \pm \sqrt{(0{,}5+B)^2 - \frac{1}{3}}\right]
\end{aligned}
\qquad (20)
$$

Empirical investigations showed that obtained simplified models ensure precision equal 15% to 20% of time constants evaluation [2].

5. EMPIRICAL INVESTIGATION OF THE STATIC AND DYNAMIC CHARACTERISTICS OF MACHINE DYNAMIC SYSTEM

Investigation of the dynamic characteristics was performed using methods of active experiment. In order to obtain time characteristics curves of output coordinates of the object during cutting the semi-finished product with blade were registered.

It is worth noting that a process of cutting product with a blade at constant values of longitudinal feed and rotational speed of a product can be considered as transient process for control value and as transient process for a disturbance. Simultaneously, first and second operation can be considered as abrupt if main cutting edge is parallel to the cut surface and thickness of the cut layer remains constant after cutting in.

Mentioned transient processes are characterized by zero initial conditions. Transient object characteristics for a disturbance with non-zero initial conditions would be registered during turning semi-finished products with abrupt change of allowance (Fig. 6).

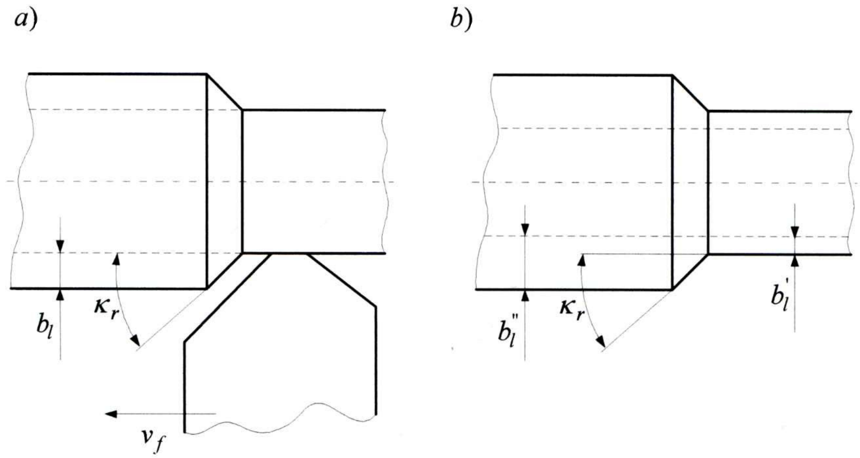


Fig. 6. Sketches of semi-finished products for determining transient function: a – controlling longitudinal feed, b – disturbance in a form of allowance [source: own study]

During experimental tests a tangent component of cutting force as object output value. To its measurement two-component dynamometer was used. Tangent cutting force moves “movable” part of the force gauge (to which blade is fitted) with respect the solid part located on a support due to elastic deformations of an element sensor of linear displacements. Results showed that value of the displacement of "movable" part with respect to the solid one, thanks to high longitudinal and radial stiffness of the element with reduced section depends practically only on the tangent cutting force.

In order to register static characteristic of the mentioned dynamometer, the blade fitted in the device using special lifting tool was loaded with a force equivalent with equivalent direction to tangent cutting force. Thanks to that dynamometer gain coefficient was found and it was established that nonlinearity of its static characteristics does not exceed 2%. Dynamic characteristics of the gauge were obtained using oscilloscopic recording of curves of transient processes caused by increase and decrease of load. Inertia of the gauge, as shown by performed experiments, is smaller by an order of magnitude than inertia of an object what allows considering the device as proportional element.

In order to obtain indicator of the beginning of transient process during oscillographic recording exactly in a moment of cutting the blade into a semi-finished product, low voltage was delivered to the blade (isolated from grip) – second pole was connected to the machine body. Moment of contacting the edge and machined semi-finished product was detected by closing mentioned electrical circuit.

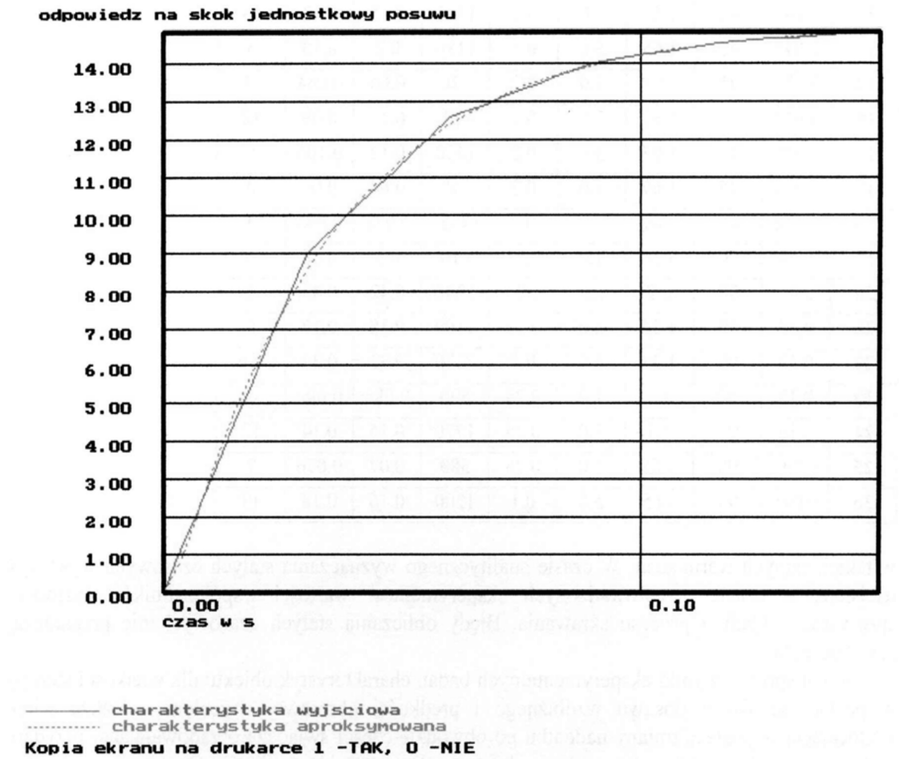


Fig. 7. Experimental transient characteristics of the control object [source: own study]

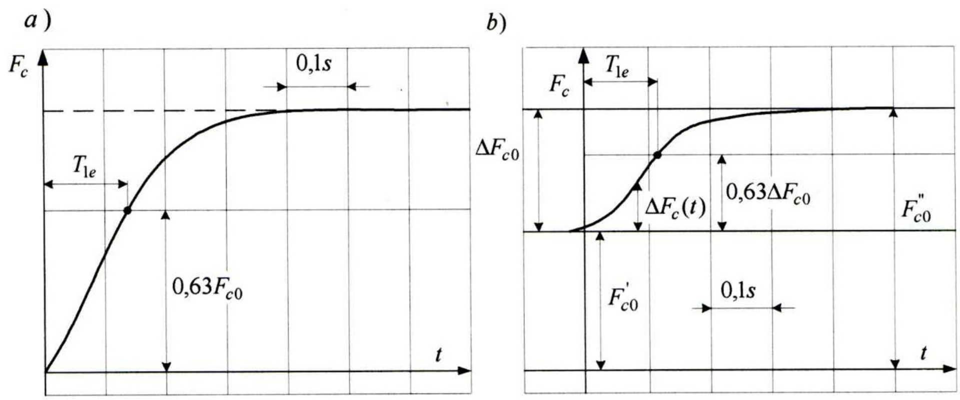


Fig. 8. Experimental transient characteristics of the control object [source: own study]

Example: Fig. 7 and 8 show oscillographs of the transient processes, obtained during experimental testing dynamic lathe system. First was obtained for cutting process in the following conditions: semi-finished product material – steel C45, blade Til5Co6, blade normal angle κ_r =90°, cutting speed v_c= 90 m/min, cutting depth a_p= 1 mm, speed of longitudinal feed v_f =60 mm/min, thickness of a cut layer in a stationary state a =0,2 mm, value of tangent cutting force in a stationary state F_{C0}=350 N, product rotation time τ =0,2 s, product diameter d=30 mm. Calculation of the cutting gain coefficients (taking into account literature data) gives m_x=0,66x10^6 N/m, m_y=0,14x10^6 N/m. Susceptibility of the semi-finished product, as shown by calculations, can be neglected in this particular case. Using static characteristics (Fig. 4 and 5) it was determined: h_{xx} =1,5x10^{-7} m/N, hyy=0,66x10^{-7} m/N. Value of the coefficient B, computed using formula (3.16), B=0,099 and approximated mathematical model can be assumed in a form of integrating element with a transition function (3.23). Response of an element to abrupt change of input value, as shown above, theoretically presents linearly increasing signal in time τ (curve 1 in Fig. 7). Real curve 2 of the output value is sufficiently close to the theoretical one; maximum deviation is 12%.

Fig. 8a shows transient characteristics obtained during cutting time in the following conditions: semi-finished product - steel C45, blade Til5Co6, κ_r=45°,v_c = 96 m/min, a_p= lmm, v_f =100 mm/min, $a=0,2$ mm, value of tangent cutting force in a stationary state F_{c0}=1450N, τ=0,12s. Similarly as above, cutting process gain and elastic system coefficients were found and value of coefficient B=1,2 was calculated. Model (3.18) should be assumed as approximated one (it takes into account value of a B parameter) in a form of non-periodic element of second order.

Time constants determined using equation (3.20) are equal T_{o1}=0,2 s, T_{o2}=0,006s. Taking into account that second time constant of an object is smaller by an order of magnitude than the first one, it can be assumed in further calculations that $T_{1p} \,^{=}\, T_{o1}$ and approximate experimental curve with exponent and establish time constant to be T_{1e} =0,18s - as a time after which output value reaches 0,63 of its value in stationary state.

Fig. 8b shows oscillograph of object time characteristics obtained during processing of a product with abrupt change of cutting depth from a_{p1}=1,5mm to a_{p2}=3mm, i.e. change of allowance by Δa_p=1,5mm. Semi-finished product - steel C45, bladeTil5Co6, κ_r=45°,v_c=98 m/min, v_f =100 mm/min, $a=0,2$ mm, τ=0,075s, value of tangent cutting force in a stationary state F'_{c0}=620N, F''_{c0}=1240N. According to the dependency described above average computed coefficient value is B=0,9. Time characteristics was approximated with an exponent with computed time constant T_{1p}=0,106s. Transient process can be characterized with non-zero initial conditions and experimental value of a time constant according to formula (3.45) equals 6%.

Listing experimental and calculated curves of transient processes was performed according to the methodology described below. Experimental time characteristics were approximated according to the following formula:

$$F_c(t) = F_{c0}\left[1 - \exp(-t/T_{1e})\right]$$

where: F_{c0} – established output value or its increment, T_{1e} – equivalent time constant determined basing on the oscillograph as a time, after which output value or its increment reaches 0,63 of value in stationary state. Found values of T_{1e} were compared with computed T_{1p} that were defined as time, after which computed transient characteristic, described by above dependencies, reaches 0,63 of value in stationary state.

Given results were obtained during processing of semi-finished products made of steel C45 with a blade Ti15Co6 working at normal angles 45^0 and 90^0. Values of time constants given in Table 1 were calculated as averaged results of three or four obtained oscillographs in steady conditions.

Table 1. Listing of cutting parameters and experimental and calculated time constants [source: own study]

Nr	**τ [s]**	**χ_r**	**V_c [m/s]**	**a_p [mm]**	**a**	**F_{c0} [N]**	**T_{1e} [s]**	**T_{1p} [s]**	**δ [%]**
1	0,48	45	0,8	2,0	0,2	900	0,59	0,55	7
2	0,48	45	0,8	3,0	0,2	1380	0,7	0,625	11
3	0,375	45	0,85	1,0	0,2	480	0,3	0,3	0
4	0,375	45	0,85	2,0	0,25	1140	0,46	0,43	7
5	0,375	45	0,85	3,0	0,2	1400	0,55	0,48	13
6	0,24	45	1,3	1,5	0,25	855	0,23	0,215	7
7	0,24	45	1,3	2,0	0,25	1150	0,34	0,28	18
8	0,24	45	1,3	3,0	0,2	1370	0,36	0,31	14
9	0,12	45	1,6	1,5	0,2	730	0,12	0,13	-8
10	0,12	45	1,6	3,0	0,2	1470	0,18	0,161	11
11	0,095	45	1,65	1,0	0,2	475	0,08	0,076	5
12	0,095	45	1,65	3,0	0,2	1475	0,15	0,13	13
13	0,095	45	1,65	5,0	0,1	1180	0,2	0,19	5
14	0,075	45	1,67	1,0	0,2	470	0,06	0,064	-7
15	0,075	45	1,67	2,0	0,2	981	0,11	0,09	18

Analytic determination of time constants was performed using values of the gain coefficients corrected by performed experiments. Errors of the computed time constants basically do not exceed 20%. Results of investigating experimental object characteristics for controlling values in a form of speed of longitudinal feed and spindle rotational speed together with disturbing value in a form of allowance on a part perimeter show that mathematical models, obtained after analytic analysis, are useful. Research confirmed introduced conclusion about possibly wide range of changes in case of control object parameters.

6. CONCLUSIONS

Structure and parameters of a control object depend on processing conditions of the machine tool. Time constants of a time object are mainly affected by delay time τ, depending on object rotational speed. Moreover, object inertia depends on a value of B coefficient. Adjustment range of the rotational speed of main motion drive in case of ordinary machines reaches 100 and more - in certain range it can change time constants of a control object.

Object gain coefficient, defined by delay time, parameters of a technological system, gain coefficients of cutting process and also can change by an order of magnitude. Simultaneously it is necessary to take into account that such wide ranges of changes of the parameters of machine dynamic systems characterize their operation in whole technological range. During realization of the part processing its rotational speed usually remains constant and changes of object parameters are caused mainly by changes of allowance what results in changed gain coefficients in cutting process. Moreover, variability of the dynamic properties of an object is affected by changes of parameters of elastic system along product axis what occurs when technological system includes non-rigid part.

Properties of the turning process like nonlinearity, variability of parameters, deterministic and accidental disturbances cause that effective controlling is not possible in case of ordinary adjustment systems. Results of research covering use of developed control models indicate that good quality control can be ensured by adapting algorithms.

REFERENCES

[1] TARANENKO V., ABAKUMOV A.: *Dinamicheskiye modeli dlya ocenki tochnosti tehnologicheskih sistem.* WNIITEMR, 1989, vyp. 1, p. 56.

[2] CZACHOR G.. TARANENKO W.: *Badania eksperymentalne charakterystyk dynamicznego systemu modułu tokarskiego.* Rzeszów. Materiały 111 Międzynarodowej Konferencji Naukowo-Technicznej – MTK 2002. Modułowe technologie i konstrukcje w budowie maszyn. Zeszyty Naukowe Politechniki Rzeszowskiej Nr 196. Mechanika z. 59, Rzeszów 2002. p.159–166.

[3] TOMKÓW J.: *Wibrostabilność obrabiarek*, WNT. Warszawa 1997, p. 205.
[4] BESEKERSKIJ V. A., POPOY E. P.: *Theory of automatic control systems*. M.: Nauka, 1975. p. 768.
[5] ABAKUMOW A., TARANENKO W., ZUBRZYCKI J.: *Program modules for the study of characteristics of the dynamie system of machining process*. Zeszyty Naukowe Politechniki Rzeszowskiej NR 230 MECHANIKA, z. 67 Modułowe Technologie i Konstrukcje w Budowie Maszyn, Rzeszów 2006, p. 99–109.
[6] ABAKUMOY A., TARANENKO V., ZUBRZYCKI J: *Modeling of characteristics of dynamic system of turning process for axial-symmetnc shafts.* V-th International Congress "Mechanical Engineering Technologies 06" (MT'06), September 20–23, 2006, Varna, Bulgaria. Procedings. Section III, p.76–78.
[7] TARANENKO W.. SZABELSKI J., TARANENKO G.: *Fundamentals of Identification of the dynamic system of turning of tow-rigidity shafts*. Pomiary, Automatyka, Robotyka. Miesięcznik naukowo-techniczny, nr 2/2008, Warszawa 2008.
[8] TARANENKO G., TARANENKO V., SZABELSKI J., ŚWIC A.: *Systemic analysis of models of dynamie systems of shaft machining in elastic-deformable condition*. Applied Computer Science, Business Process Optimization, vol. 3, no. 2, 2007, Technical University of Zilina, Slovak Republic.
[9] TARANENKO W., CZACHOR G.: *Badania eksperymentalne charakterystyk układu dynamicznego modułu tokarskiego.* Modułowe technologie w konstrukcji maszyn. MTK'02 15-18 październik 2002. Rzeszów 2002.
[10] ZUBRZYCKI J.: *Zwiększenie dokładności wiercenia wibracyjnego głębokich otworów.* Wyd. Lubelskie Towarzystwo Naukowe, Lublin 2014.
[11] ABAKUMOW A., TARANENKO W., ZUBRZYCKI J., TARANENKO G.: *Identyfikacja i sterowanie układem dynamicznym obróbki skrawaniem.* Wyd. Politechniki Lubelskiej, Lublin 2014.

Lucia Koukolová[1], Rudolf Jánoš[2]

ROBOTIC REHABILITATION – THE THERAPY USING ROBOTIC SYSTEMS

1. INTRODUCTION

It is a general assumption that robotics will play an important role in therapy activities within rehabilitation treatment [6,8]. In the last decade, the interest in the field has grown exponentially mainly due to the initial success of the early systems and the growing demand caused by increasing numbers of stroke patients and their associate rehabilitation costs [2,5]. As a result, robot therapy systems have been developed worldwide for training of both the upper and lower extremities.

Stroke is the third most frequent cause of death worldwide and the leading cause of permanent disability in the Europe and USA. Neurological impairment after stroke frequently leads to hemiparesis or partial paralysis of one side of the body that affects the patient's ability to perform activities of daily living such as walking and eating. Physical therapy, involving rehabilitation, helps improve the lost functions. One third of surviving patients from stroke do not regain independent walking ability and those ambulatory, walk in a typical asymmetric manner. Rehabilitation therapies are critical to recover, and therefore many researches is ongoing on the field.

The goal of rehabilitation exercises is to perform specific movements that provoke motor plasticity to the patient and therefore improve motor recovery and minimize functional deficits. Movement rehabilitation is limb dependent, thus the affected limb has to be exercised.

Robotics for rehabilitation treatment is an emerging field which is expected to grow as a solution to automate training. Robotic rehabilitation can:

- replace the physical training effort of a therapist, allowing more intensive repetitive motions and delivering therapy at a reasonable cost,
- assess quantitatively the level of motor recovery by measuring force and movement patterns.

[1] Technical University of Kosice, Faculty of Mechaical Engineering, Departemnt of Robotics, B. Nemcovej 32, Kosice, Slovakia, e-mail: lucia.koukolova@tuke.sk
[2] Technical University of Kosice, Faculty of Mechaical Engineering, Departemnt of Robotics, B. Nemcovej 32, Kosice, Slovakia, e-mail: lucia.koukolova@tuke.sk

2. THE HISTORY

Most reviews of work in the field of Rehabilitation Robotics cite work going back to the early 1960's. Since then many projects have taken place. Some have come and gone with few obvious positive results, some have been an ongoing development process, while a few have resulted in marketable products which are widely benefiting disabled people. All have, however, contributed to the volume of knowledge from which those now working in this field of research benefit. In some cases the problems which have defeated earlier researchers may now be overcome by the application of current technology and understanding.

The first referenced rehabilitation manipulator was the CASE manipulator, built in the early 1960's. This was a powered orthosis with four degrees of freedom, which could move the user's paralysed arm. Another early powered orthosis was the Rancho Los Amigos manipulator [3] with seven degrees of freedom.

Work in the more specific area of rehabilitation robotics started in the mid 1970's. One of the earliest projects was the workstation based system designed by Roesler [9] in Heidelberg, West Germany. The purpose designed, five degree of freedom manipulator was placed in a specially adapted desktop environment, using rotating shelf units.

Another early workstation system was that of Seamone and Schmeisser at the Johns Hopkins University, supported by the Veterans Administration in the United States from 1974 [7]. The arm of this system was based around an electrically powered prosthetic arm, mounted on a horizontal track. Various items of equipment (e.g. telephone, book rest, computer discs) were laid out on the simple but cleverly designed workstation table and could be manipulated by the arm using preprogrammed commands.

In France the Spartacus robot [4] was based around a large high quality manipulator from the nuclear industry. With such a potentially powerful device, safety had to carefully considered and early training of users was done with the arm behind a clear screen. This project has led to the Manus project in Holland and the Master project in France, which will be described later in the text.

Another early project in the United States (1970's) was the work of Mason [1] at the Veterans Administration Prosthetics Center in New York. This was the first use of a robot arm mounted to a wheelchair, potentially offering much greater freedom than a workstation mounted system. The four degree of freedom arm was beautifully engineered, and its novel telescoping design allowed it to reach to the floor or the ceiling.

3. ROBOTIC REHABILITATION

Robotics rehabilitation is often only thought of as robotic aids to assist people handicapped by a manipulative disability. However, recent research in rehabilitation robotics reveals more extended possibilities for the use of robot technology in rehabilitation. Hillman defined rehabilitation robotics as the application of robotic technology to the rehabilitation needs of people with disabilities as well as the growing elderly population. This extended definition includes augmentative mobility, robots for therapeutic training and robots for help care-givers.

A large number of industrial robots are used to manufacture products worldwide. On the contrary, only hundreds of rehabilitation robots are practically used by people with disabilities. This indicates that successful rehabilitation robots cannot be realized with application of only industrial robotic technologies. Rehabilitation robotics has many technical and non-technical problems. First, cost and maintenance are the most serious problems for popularization.

Second, rehabilitation robots are used close to users and because of this proximity accidents can happen. To avoid injury to the end user, recent rehabilitation robots are designed to operate with extremely low power. This means that they can only work with light goods and can only move very slowly. Consequently, the tasks they can perform are very limited.

Third, most users have physical or mental handicaps, making it difficult for them to operate a robot. An effective human interface is one of the key technologies for rehabilitation robotics. At present, the only way to adapt an interface to each user's various needs is through trial and error. Systematic adaptation should be developed in the future.

4. BASIC DIVISION OF ROBOTIC REHABILITATION SYSTEMS

Because of the ageing of our population, there is a growing necessity for new technologies that can assist the disabled and elderly in their daily living. There are two main arguments for this. First, it is expected that countries will face a tremendous shortage on staff and qualified healthcare personnel in the near future. Second, people prefer more and more to live in their own homes as long as possible instead of being institutionalized in sheltered homes, or nursery homes when problems related to ageing appear. To address these issues, we not only need sufficient health care personnel, but also the presence and appliance of high-tech devices. ICT technology and robotics are developing quickly nowadays, resulting in products that have the potential to play an important role in assisting to the disabled and elderly. In order to use new technology in an effective and efficient way, robust information with respect to their effects is needed, especially when used in healthcare.

Robotic rehabilitation systems consist of two main types of rehabilitation robots. They can be distinguished by the mechanism of human-robot interaction and the number of segments which the robot can directly “control”: robotic manipulandum and robot orthoses. The basic division of robotic rehabilitation systems is displayed at the figure 1.

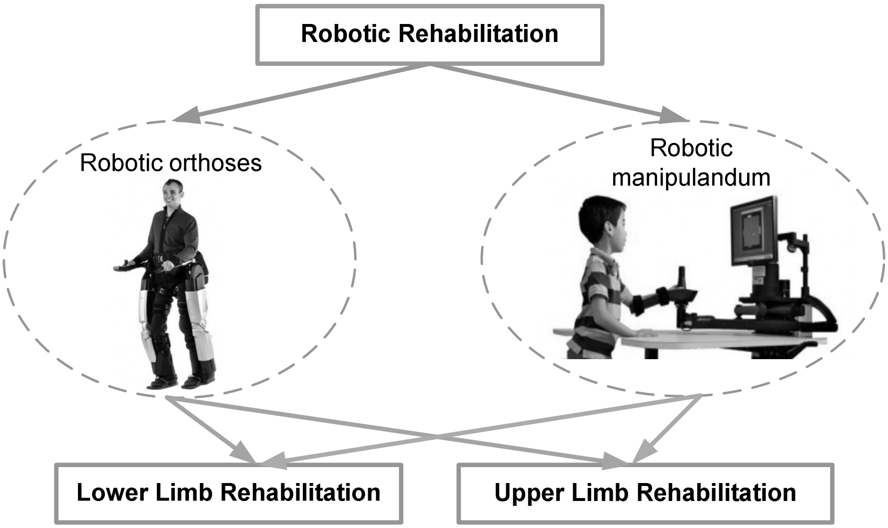


Fig. 1. Categorization of rehabilitation robots [source: own study]

Robotic manipulandum are often adapted from industrial robots with more or less degrees of freedom (DoF) but only one point of physical contact between the distal and of the limb and the extremity of the robot (for example, the patient holds a handle or has the forearm strapped to a support). In this category, there are two subcategories: traditional manipulandum (such as the MIT Manus, or the Bi-Manu Tract) and cable manipulandum. The MIT Manus is the most famous and has been the object of the most clinical trials. It is a 2 DoF manipulandum with which the patient can interact to make planar pointing movements. During the session, the patient´s arm is supported in a non-motorised orthosis and he holds the handle of the manipulandum. Cable robots resemble the classical pulleys used in therapy (NEREBOT, MARIBOT, Kinehaptique, Gentle/s). These types of robots impose forces or positions or provide assistance at the point of contact between the patient and the machine but only at this point. They cannot, therefore, directly control the different movements synergies used by patients in order to achieve the displacement of the endpoint.

More recently, robotic orthoses have begun to be developed. These orthoses allow contact at several key points of the limb and can therefore control the different segments of the limb. This means that they can influence coordination patterns and/or better follow the particurities of the patient´s postures of movements. There are also two sub-groups in this category: anthropomorphic robots which are in contact practically with the whole limb (exoskeletons such as ARMin, RUPERT) and robots which have discontinuous contact with the limb (ARMguide, Dual Robotic Systems from Leeds).

5. CONCLUSIONS

Robotic systems are believed to be used as standard rehabilitation tools in the near future. The capacity of robots to deliver training with high intensity and repeatability make them very valuable assistant tools to provide high quality treatment at a lower cost and effort. These systems should also be used at home to allow patients to perform therapies independently, not replacing the therapist but supporting the therapy program.

Acknowledgements

Paper is the result of the project implementation: KEGA 059TUKE-4/2014 "The Development of quality of life, creativity and motor functionalities of disabilities and older people with support of robotic devices."

REFERENCES

[1] BENIAK J.: *Monitoring of operational load of disintegrative machines.* Applied Mechanics and Materials, vol. 309, 2012, pp. 88–95, ISSN: 1660-9336.

[2] GOLA A., SOBASZEK Ł.: *Simulation of production flow using Matlab system.* [in:] Lipski J., Świć A., *Optimization of production processes,* Wyd. Politechniki Lubelskiej, Lublin, 2013, p. 64–74.

[3] HILLMAN M.: *Rehabilitation robotics from past to present – a historical perspective.* Proceedings of the ICORR 2003.

[4] KOUKOLOVÁ L.: *The development of rehabilitation robot.* Transfer inovácií 29/2014, p. 195-198.

[5] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning.* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[6] PILAT Z., KLIMASARA W. J., JUSZYŃSKY L., MICHNIK A.: *Research and development of rehabilitation robotics in Poland.* Applied Mechanics and Materials, vol. 613, p. 196–207.

[7] ROBERTSON J. V. G., JARRASSÉ N., ROBY-BRAMI A.: *Rehabilitation robots: a compliment to virtual reality.* Schedae 2010, Prepublication no. 6, Fascicule no. 1., p. 77–94.

[8] ŚWIĆ A., GOLA A.: *Economic Analysis of Casing Parts Production in a Flexible Manufacturing System.* Actual Problems of Economics, no. 3 (141) 2013, p. 526–533.

[9] TEJIMA N.: *Rehabilitation robotics: a review.* Advanced Robotics, vol. 14, no. 7, 2000, p. 551–564.

Zbigniew Nawrat[1]

ROBIN HEART SURGICAL ROBOT

1. INTRODUCTION

The initiated by the author project results are the family of Robin Heart robot and universal mechatronic tools series Robin Heart Uni System for use during minimally invasive surgery on the heart and other soft tissues. The number of endoscopic procedures, less invasive than traditional surgery, performed through natural orifices in the patient's body, or through special openings called ports, is on the rise. The purpose of robots is to improve efficiency, repeatability (standardization) and reducing the invasiveness of surgical procedures (extension of the group of patients for whom successful surgical intervention is possible). Robot is intended to keep the surgeon in the most comfortable, dexterous and ergonomic position [1].

The **robot** is one of the few words of Slavic origin, which entered the global language of modern science and technology. Medical robotics, as the technical discipline, deals with the synthesis of certain functions of the physician or nurse by means of using some mechanisms, sensors, actuators and computers. Medical robotics includes the manipulators and robots dedicated to support the surgery, therapy, prosthetics and rehabilitation.

Currently several types of medical robotic systems are applied in the surgery, including: robots replacing the assistant during the operation – like AESOP, EndoAssist or Polish prototype Robin Heart Vision; surgical robots – like Zeus, da Vinci or Polish prototype Robin Heart. The robot, or actually a "tele-manipulator", is the first ever tool capable of assisting a surgeon by providing the capability to directly use surgery simulation and planning methods [1].

[1] Name of University, Foundation of Cardiac Surgery Development, Zabrze & Medical University of Silesia, Katowice, www.robinheart.pl, www.medicalrobots.eu, nawrat@frk.pl

2. ROBIN HEART

Several models of the robot have been developed, differing in control and mounting systems. Spherical model was created (2001), Robin Heart 0 (2002), a prototype of Robin Heart 1 and model of Robin Heart 2 (2003), Robin Heart Vision (2008) and Robin Heart mc^2 (2010) (Fig.1) and more than 200 publications and presentations at scientific conferences have been prepared till now [1].

The Robin Heart 0 and Robin Heart 1 have an independent base and are controlled via an industrial computer and specialist software. The Robin Heart 2 is fixed to the operating table and has two arms, on which one can fix various surgical instruments. The control system uses its own software as well as signal and specialist microprocessors. Thanks to its modular structure, it can be adjusted for surgery of different types. The Robin Heart Vision, will become the surgeon's partner in the operating room next year. It will replace a human assistant who usually holds the endoscope to enable the observation of the operative field of laparoscopic instruments. The Robin Heart Vision is easy to use and install, and will be conveniently carried in a suitcase [1].

The process of projecting a robot starts by determining the tool-tissue reaction (mechanical characteristic, the forces for specific operations, dynamic analysis of the work of a tool) and the person-tool/man-machine contact (kinematic analysis of the surgeon's motion). The surgeon's motion and tool trajectory in natural environment are analyzed with the use of optical biometry techniques. The forces applied during the impact of tools on tissue during typical surgical activities are measured. The construction assumptions as well as the functionality and ergonomics of the innovative tools can best be verified by means of video-recording. As a result, a user-friendly surgical work station and an efficient surgical tool are constructed [1].

The Polish heart surgery robot is an original design. Thanks to its modular structure, it can be adjusted for surgery of different types. The Robin Heart Shell console is equipped with a consulting program that makes it possible to obtain all patients diagnostic information during the operation, as well as elements of operation planning on the screen (Fig.2). The virtual operating theatre (Fig.1) introduced in our laboratory allows surgeons to train some elements of an operation, check the best placement of the ports in order to avoid internal collisions. Exhausted by 3-D visualisation, this system can be helpful in planning of a operation on a given patient. New, semi-automatic tools are in the process of emerging- our Robin Heart Uni System [2].

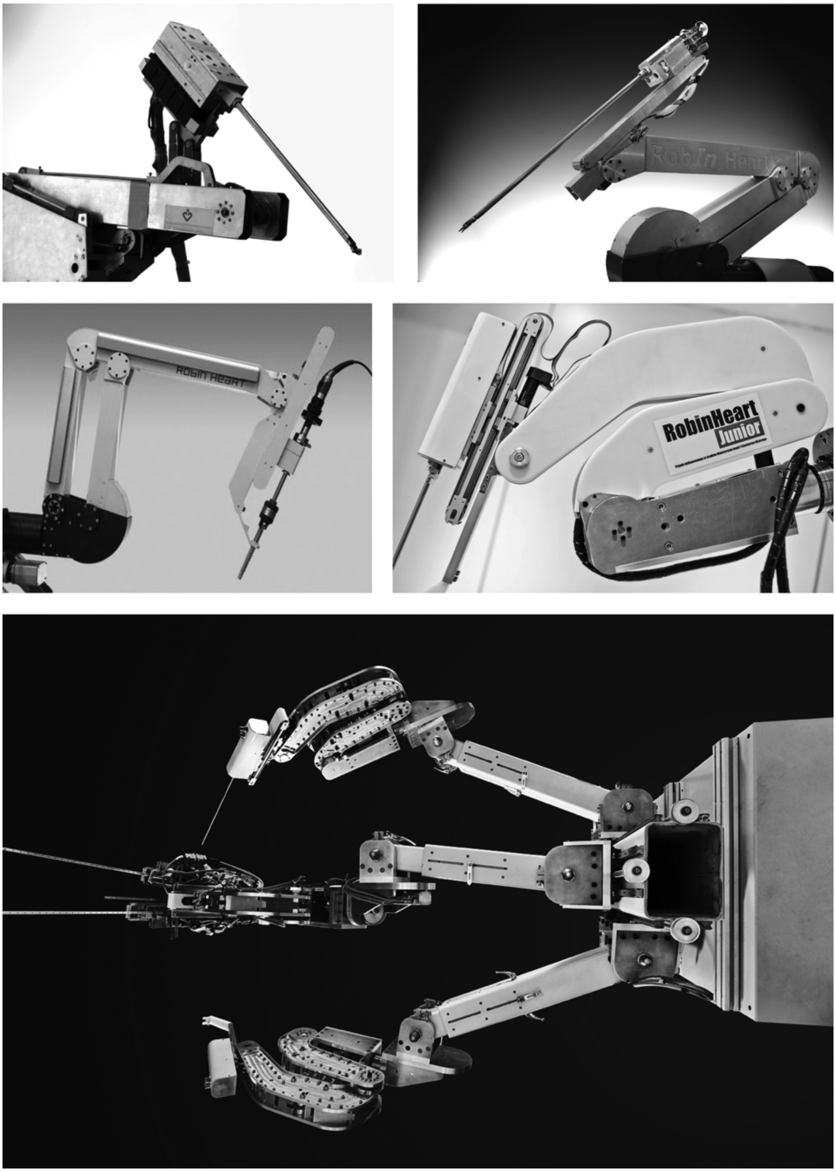


Fig. 1. The Robin Heart family robots: Robin Heart 0, Robin Heart 1, Robin Heart 2, Robin Heart Vision, Robin Heart Junior, Robin Heart mc^2 [source: own study]

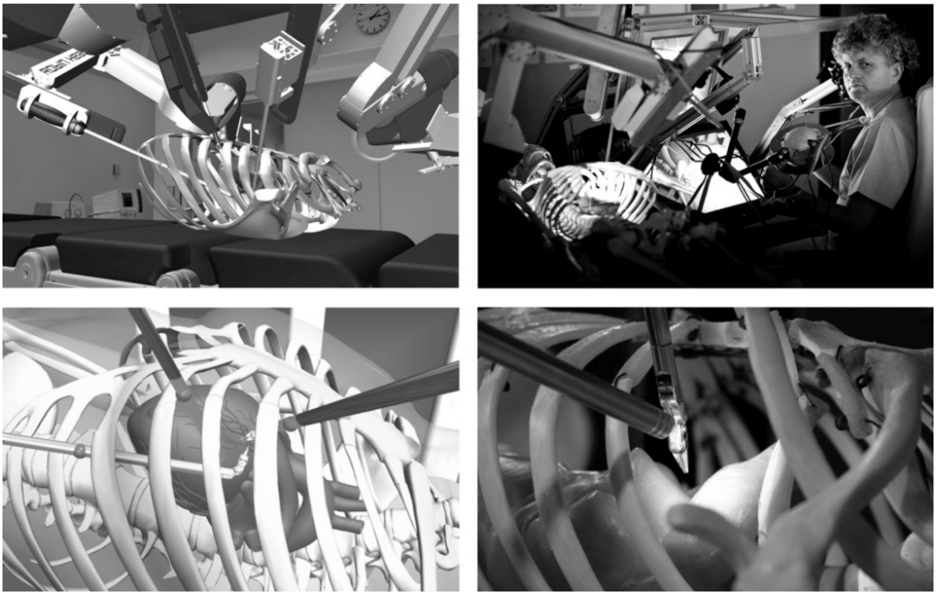


Fig. 2. Virtual and real condition for testing the Robin Heart robot [source: own study]

Using a Virtual Reality technology an interactive model of surgery room equipped with a Robin Heart system was created using EON Professional software. This computer modelling method allows for an advance procedure training and will be used as a low cost training station for surgeons in the future. Model allows for a better understanding process of less invasive surgery treatment and a robot behaviour. The link between this type of modelling and a Computer Aided Design (CAD) techniques is using an accurate CAD robot models in a VR software together with a precise reflection of workspace geometry. This approach gives a surgeon easy and intuitive way to understand a technical information and use it to optimize and plan medical process. Presented model of Operating Room in Virtual Reality environment has been performed in FCSD and successfully used from 2006.

The process of developing the robot starts from the determination of the tools- tissue reaction (mechanical characteristic, the forces for specific operations, dynamic analysis of tools work) and person – a tool and then man-machine contact (kinematic analysis of surgeon motion) analyzing. The laboratory Fig. 3 and vivo testing Fig. 4 procedures and methods have been prepared and different study have been performed.

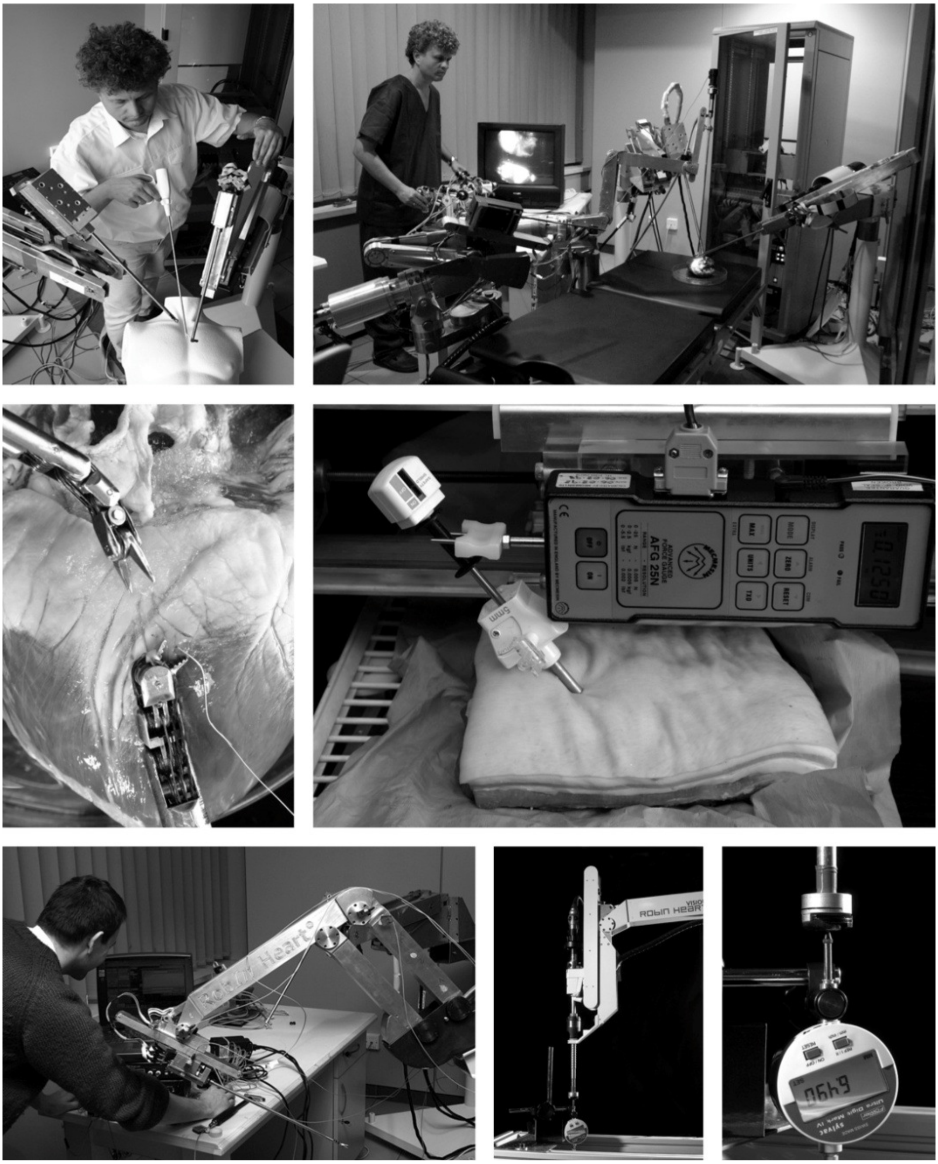


Fig. 3. The comparison of different tolls (Robin Heart 0,1 and laparoscopic tool). The test using animal tissue. Evaluation of Robin Heart robot is carried out using measurement of vibration (new accelerometer sensors), linear movement measurement using digital micrometer [source: own study]

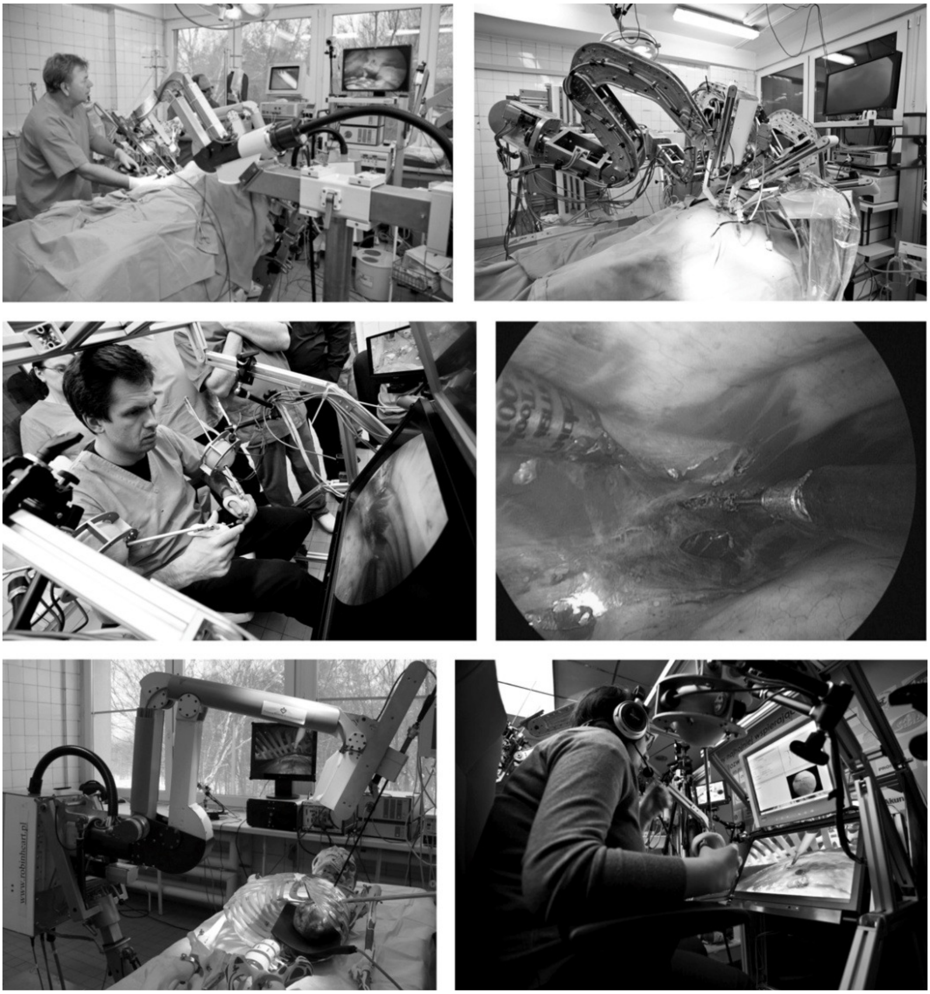


Fig. 4. Research. The first experiments on animals with robots from the family Robin Heart (chole-cystectomy and heart valve surgery) at the Center for Experimental Medicine, Medical University of Silesia were carried out. Animal tests using New Robin Heart robot mc^2 (mammary artery harvesting and bypass surgery) were carried out. Bottom – teleoperation on tissue model in human phantom at distance Zabrze (FRK)–Katowice (CMD SUM) [source: own study]

The Robin Heart manipulator has very good and relatively large working space, in which surgeon can select small subspace with very good isotropic kinematics' properties for manipulating of objects with good position accuracy. System was verified both functionally and technically. Standard technical evaluation allowed to estimate the value of positioning resolution equal 0.1 [mm] [2]. The mile stone of the project were an animal experiment, carried out in January 2009 (Robin Heart model 1, 2, Vision) and May 2010 (Robin Heart mc^2) (Fig.4). Robin Heart system experiment carried out on pigs allowed to verify many aspects of very complex project and was the source of hints for future development. A pre-operation planning stage included surgeon trainings on physical and virtual anatomy models with the usage of real pig tissues. A common control system for all three robotic arms was created PXI bus hardware, working in real time operating system, controlled by software written in LabView environment.

Elements of operations in the abdomen and heart cavities were successfully performed. Robin Heart mc^2 creates a completely new job opportunities for surgeon - both in the local area and globally. It can be compiled as an arm of the platform (a small robot with two endoscopic tools and endoscope for observation) or as telemanipulator working for three people - the mean surgeon and his assistant, and an assistant holding the endoscope (controlled from console by one operator). It is really new solution for robotically assisted surgery (Fig.1). The first model of teleoperation have been performed in December 2010 between Zabrze (FCSD) and Katowice (CEM) successfully. In next experiments we test system also at Zabrze-Cracow and Zabrze-Mexico City distance.

The goal of Robin Heart PortVisionAble project is to develop first fully functional model of compact, mobile telemanipulator for steering the vision channel of MIS with telemedic system allowing remote picture from operation field sending. After series of studies and tests of this model three corrected prototypes will be prepared, ready to clinical examinations (Fig. 5).

Robin PVA, lightweight, portable and inexpensive robot can replace one of the assistants at the mini-invasive surgery and enable the distance-participation of both experts/advisor or student during surgery. We can make a robot model to the full technical and functional tests, and then, after verification of the project, three prototype robots ready for clinical trials. Developed research and technological documentation may be used to start the series production and clinical implementation of this robot. The first prototype Robin Heart PVA 0 was presented during Medical Robotics Conference in Zabrze in December 2014 (Fig.6).

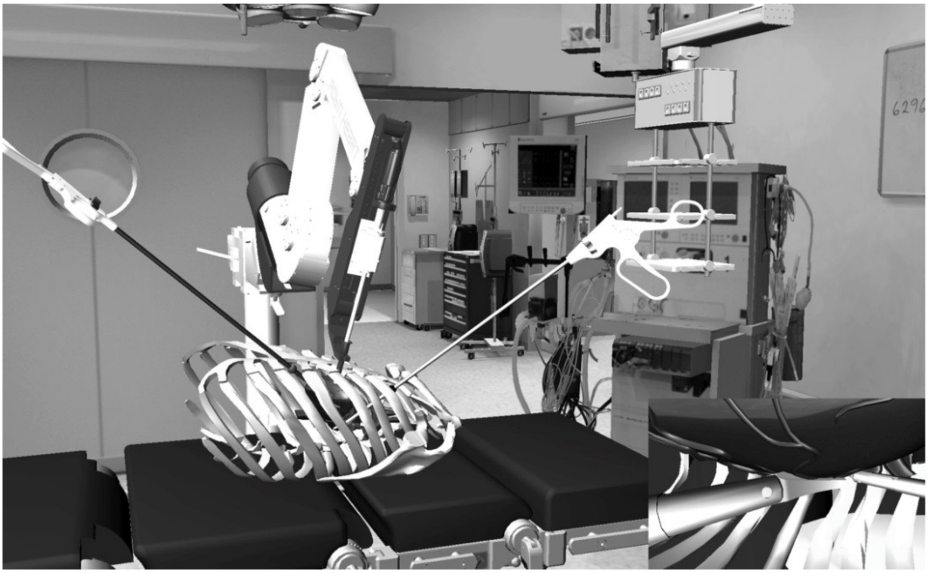


Fig. 5. The virtual model of the Robin Heart Vision application [source: own study]

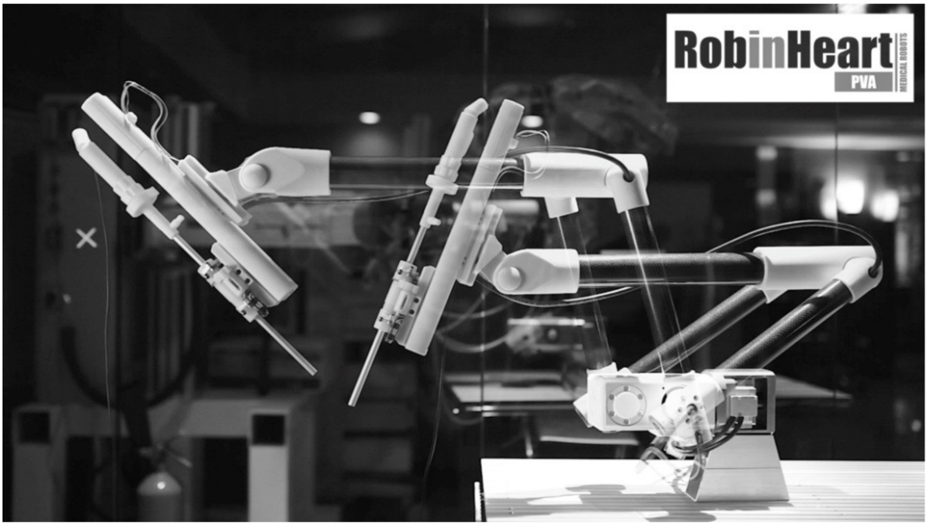


Fig. 6. The first prototype Robin Heart PVA 0 – new technology for improve functional achievements of Polish robot [source: own study]

3. DISCUSSION – ETHICS & MARKET

Recent history shows that medical robots proved to be needed by surgeons to allow them to operate less invasively, more precisely and safely, sometimes across great distances.

In these areas medical robots extend the reach of physician's hands and allow for more effective action inside the human body.

More generally – robots are needed by people and by healthcare systems. Even a back of the napkin calculation reveals that we soon will not be able to address the demands of home care without the help of new technologies. Medical-social robots are the only systems capable of delivering effective remote care (when remotely controlled by a physician) or even autonomous decision making and patient interaction [4].

In Poland the number of people, who are unable to live independently and require care is estimated to be between 1.6 and 2M (as of 2011). We only have 120,000 physicians and only 80,000 of them are actually practising physicians. This means that a patient-to-physician ration is just 1000:2. The situation of other medical personnel is not much better, we only have 250,000 nurses [4].

It is estimated that by 2035 over 9.6M people will be above 60 years old. According to Central Statistical Office 27% of our society will be in post-productive age. We will have to turn to robots for help. Robotic assembly lines have saved the mass production of cars and improved the standardisation of products manufacturing while lovering the prices and improving the work efficiency. Isn't that exactly what is needed in healthcare?

Certain changes are already visible. In the recent report by the International Federation of Robotics 2013 it is said that "The total number of professional service robots sold in 2012 rose by a relatively low 2% compared to 2011 to 16,067 units up from 15,776 in 2011. Sales of medical robots increased by 20% compared to 2011 to 1,308 units in 2012, accounting for a share of 8% of the total unit sales of professional service robots. The most important applications are robot assisted surgery and therapy with 1,053 units sold in 2012, 6% more than in 2011. The total value of sales of medical robots increased to US$ 1,495 million, accounting for 44% of the total sales value of the professional service robots".

In 2014 report we will find: "Sales of medical robots decreased by 2% compared to 2012 to almost 1,300 units in 2013, accounting for a share of 6% of the total unit sales of professional service robots. The most important applications are robot assisted surgery and therapy with more than 1,000 units sold in 2013, 2% less than in 2012. The total value of sales of medical robots increased to US$1,450 million, accounting for 41% of the total sales value of the professional service robots. Medical robots are the most valuable service robots with an average unit price of about US$1.5 million, including accessories and services. Therefore, suppliers of medical robots also provide leasing contracts for their robots."

From this report: Projections for the period 2014-2017: About 1,140 robots for rescue and security applications will be sold between 2014 and 2017, mainly surveillance and security robots. Robots for professional cleaning will increase to about 2,550 units in the same period, mainly systems for floor cleaning. About 7,130 medical robots will be sold plus 3,850 robots for inspection and maintenance.

Which leads to an obvious conclusion – a revolution has already begun.

4. ISMR – INTERNATIONAL SOCIETY FOR MEDICAL ROBOTICS

In Zabrze was founded International Society for Medical Robotics ISMR. The Society's objectives are:

- support of the development and dissemination of knowledge of medical robotics;
- support of the advancement of medical and technical sciences, in particular: surgery, cardiac surgery, mechatronics, information technology and telecommunication, automatics, robotics and other related fields.

The official ISMR website is www.medicalrobots.eu. All information about Robin Heart Team activity can be found on www.robinheart.pl

The results of Polish project Forsight studies indicate that the medical robotics has the highest priority, but the importance of social and business risk.
To make robotically-assisted surgery wider acceptable the operation have to be more easier and more attractive for the end user – surgeon (new tolls, pre-planning, advisory system) and less expensive for hospital owner. It seems attainable in near future -if only monopolistic and conservative tendencies commercial firms will not take above spirit of inventiveness and spontaneous interest which we can observe in many scientific centres and academical in Europe [3].

10 years of Polish medical robotics was a time of high activity and scientific research, particularly in the field of robot for surgery and rehabilitation. We hope that the time is near the first clinical application and market launch.

5. CONCLUSIONS

The Robin Heart system includes the planning system, training system, experts' program, as well as tele-manipulators and automatic surgical tools. We plane the first clinical application of endocamera arm: Robin Heart

PortVisionAble, robotically controlled in 2015. The Robin Heart family of Polish robots has a chance of becoming a commonly used high-tech technical and tele-medical system facilitating the performance of some parts of operations in minimally invasive, precise manner, safe for the patient and the surgeon.

Acknowledgements

Robin Heart Project was supported by KBN 8 T11E 001 18 and projects: PW-004/ITE/02/2004, R1303301 and R13 0058 06/2009, and NCBR - the national Centre for Research and Development - grants: R1303301 and R13 0058 06/2009, Robin PVA – no 178576,TeleRobin – no 181019 and many sponsors. The project of flexible tool supported in part by the European Commission within the STIFF-FLOP FP7 European project FP7/ICT-2011-7-287728.

Thanks to EMED company from Warsaw and Famed-Zywiec, the group of prof. Leszek Podsedkowski from Lodz University of Technology and Marek Ciembroniewicz – EMSI, Swietochlowice. Special words of appreciation to Surgeons: dr Joanna Sliwka-Los, dr Michal Zembala (SCHS, Zabrze), dr Grzegorz Religa (Warsaw), dr Romuald Cichon (FRK, Zabrze) and our team: Krzysztof Lis, Krzysztof Lehrich, Lukasz Mucha, Paweł Kostka, Zbigniew Małota, Kamil Rohr, Wojciech Sadowski, Krzysztof Krzysztofik, Piotr Rybka, Dariusz Krawczyk, Mariusz Jakubowski, Adam Klisowski.

REFERENCES

[1] NAWRAT Z.: *The Robin Heart Story Medical Robotics Reports,* 1/2012, p. 19–21.

[2] NAWRAT Z., KOSTKA P.: *Robin Heart – Perspectives Of Application Of Mini Invasive Tools In Cardiac Surgery*. Medical Robotics. Ed. V. Bozovic. Vienna: I-Tech Education And Publishing 2008, p. 265–291.

[3] NAWRAT Z.: *State Of The Art In Medical Robotics In Poland: Development Of The Robin Heart And Other Robots.* Expert Review Of Medical Devices, Jul 2012, vol. 9, no. 4, p. 353–359.

[4] NAWRAT Z., KAWALSKI M.: *Questions About A New Ethics – Ethics Of Medical Robots Era.* Medical Robotics Reports, 2/2013, p. 22–25.

Jozef Varga[1]

THE PROPOSAL OF WALKING PHASES FOR TWO-LEG ROBOT

1. INTRODUCTION

In this paper are described basic principles of the kinematical structure design for walking robots [6,7,9]. The article deals with the design of walking phases detailed, which is described in sagital and frontal plane so that movement of the centre of gravity was outside the support polygon and also offers the model of walk for the concrete construction of the walking robot [11]. This article is the result of research activities of our department in humanoid robotics.

2. THE PROPOSAL OF HUMANOID'S LOWER LIMB PHASES OF WALKING

The proposalof walking structure for the robot with twelve-grade movement freedom of lower legs is shown at the picture figure 1**.** It is a stationary steady way of walking, where in every moment of system's movement the robot's centre of gravity (CoG) will be above the bearing surface of foot, shown at the same picture.

This modified walking has significantly smaller claim to control and mathematical depiction. The walk has in this design firmly determined step's parameters, which are during the walking unchangeable [3,5,10]. The step cycle is divided into 13 phases. In individual phases of robot's step the legs occur in bearing or in transferable phases, in which they change their position in space [8]. The individual end parts and knots are in motion in elliptical, circular and linear trajectories, which are bound in motion of kinematic structure's end point [1,2,4].

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotic, Letna 9, 04200, Košice, Slovakia, e-mail: jozef.varga.2@tuke.sk

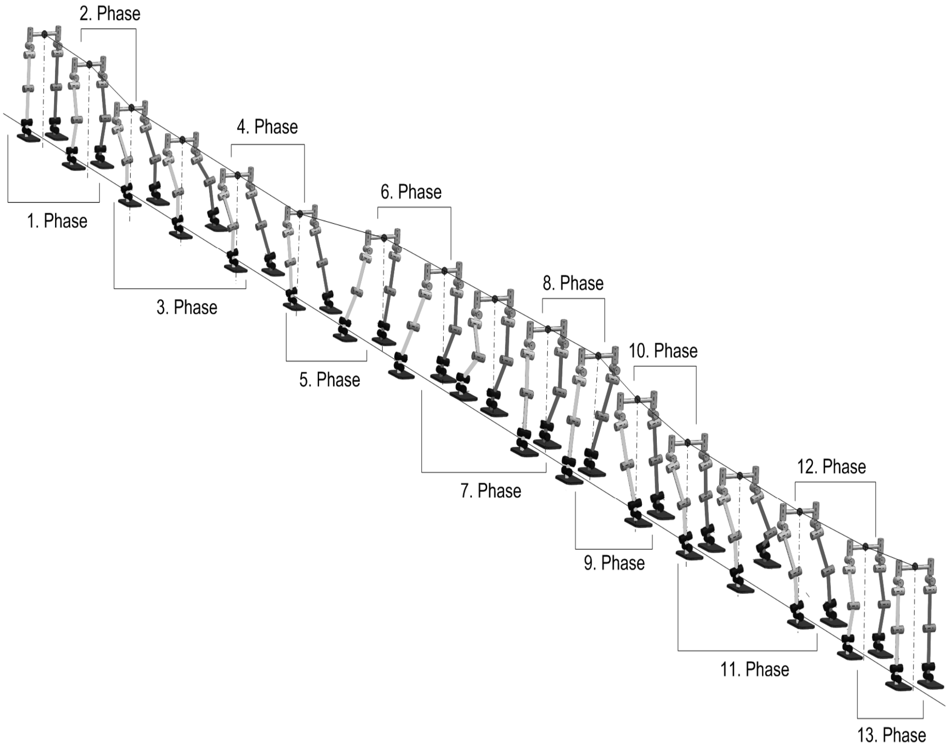


Fig. 1. Kinematical model of walking robot in real time for 13 phases [source: own study]

3. KINEMATIC SCHEMES OF WALKING ROBOT

Known are the parameters of the end element trajectories of the kinematic chain and applying the goniometrical functions and cosine theorem calculated can be the angular displacement of the individual robot joints, shown on Fig. 2 and Fig. 3. Application of the vector method calculation of the angular co-ordinates significantly simplified the overall calculations of the robot movements and the drives control as well. To illustrate the calculation was chosen phase No. 3 set off by left leg, because in this phase is showed the motion trajectory of robot's leg.

The step length used in the calculation is $\boldsymbol{k}$ = 240 mm. during the transfer phases of legs the ankle with the foot move parallel with the support along ellipse with the shorter axis 30 mm long, and therefore the step height is $\boldsymbol{d}$ = 30 mm. The length of the thighbone is **a** = 110 mm, length of calf bone is $\boldsymbol{c}$ = 110 mm and distance of the hip joint is $\boldsymbol{p}$ = 115 mm.

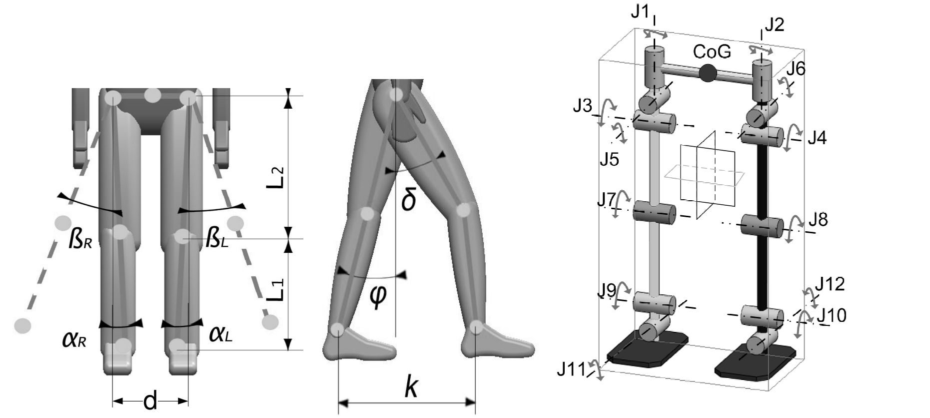
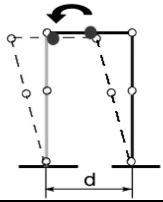
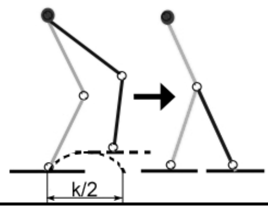
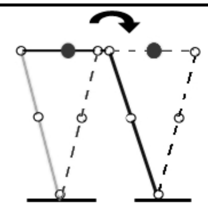
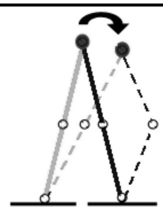
Kinematic scheme of designed robot					
 Blue line of plane is FRONTAL plane; Red line of plane is SAGITAL plane; Green ine of plane is TRANSVERZAL plane					
Phase	**Plane**	**Representation**	**Phase**	**Plane**	**Representation**
1. Move to crouch	**S**		**2. Tilt right**	**F**	
axis in motion	J3 J4 J7 J8 J9 J10			J5 J6 J11 J12	
axis at rest	J1 J2 J5 J6 J11 J12			J1 J2 J3 J4 J7 J8 J9 J10	
3. Sidestepping left foot	**S**		**4. Straightenin g the right leg at the knee**	**S**	
axis in motion	J4 J8 J10			J7 J9	
axis at rest	J1 J2 J3 J5 J6 J7 J9 J11 J12			J1 J2 J3 J4 J5 J6 J8 J10 J11 J12	
5. Tilted to the left leg	**F**		**6. Sinking hip**	**S**	
axis in motion	J5 J6 J11 J12			J3 J4 J7 J8 J9 J10	
axis at rest	J1 J2 J3 J4 J7 J8 J9 J10			J1 J2 J5 J6 J11 J12	

Fig. 2. Phases of walking robot (1–6) [source: own study]

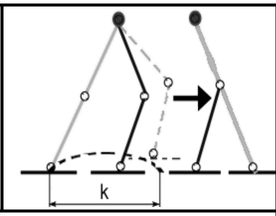
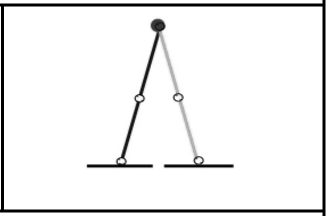
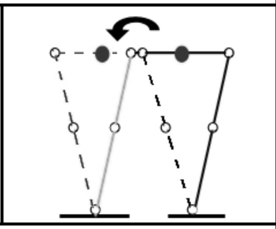
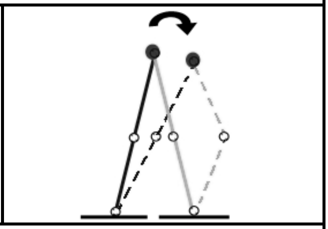
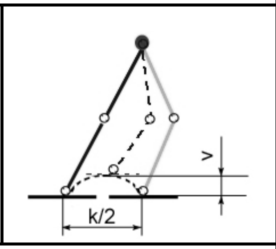
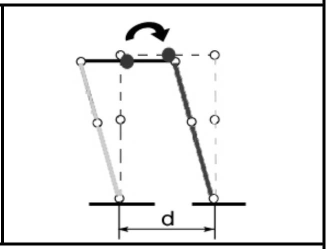
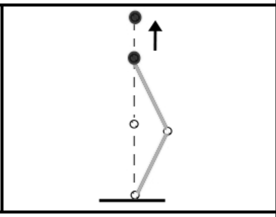
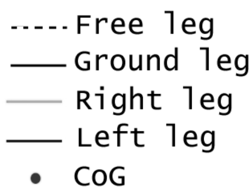
Kinematic scheme of designed robot					
7. Sidestepping the right foot	**S**		**8. Hip pitch**	**S**	
axis in motion	J3 J7 J9			J3 J4 J7 J8 J9 J10	
axis at rest	J1 J2 J4 J5 J6 J8 J10 J11 J12			J1 J2 J5 J6 J11 J12	
9. Tilted to the right leg	**F**		**10. Sinking hip**	**S**	
axis in motion	J5 J6 J11 J12			J3 J4 J7 J8 J9 J10	
axis at rest	J1 J2 J3 J4 J7 J8 J9 J10			J1 J2 J5 J6 J11 J12	
11. The inflow of the left foot robot	**S**		**12. Straightening robot**	**F**	
axis in motion	J6 J8 J10			J5 J6 J11 J12	
axis at rest	J1 J2 J3 J4 J5 J7 J9 J11 J12			J1 J2 J3 J4 J7 J8 J9 J10	
13. Straightening legs robot	**S**		**Legend:** 		
axis in motion	J3 J4 J7 J8 J9 J10				
axis at rest	J1 J2 J5 J6 J11 J12				

Fig. 3. Phases of walking robot (7–13) [source: own study]

4. CENTER OF GRAVITY MOVEMENT

The proposal of walking robot on Fig. 4 show static stability of each phases in transversal and sagital plane. That means, orthogonal projection of CoG in transversal plane is placed above support surface – one foot or two feet.

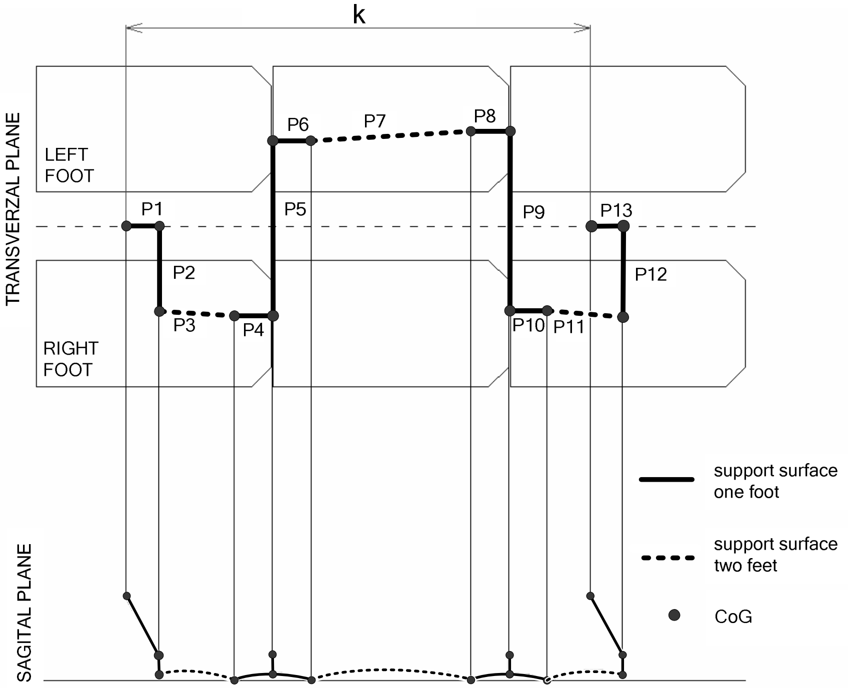


Fig. 4. Center of Gravity movement of walking robot [source: own study]

Curved line of CoG movement shown on Fig. 4 described CoG movement of walking robot during the cycle (13 phases).

5. CONCLUSIONS

In this paper was describing the principle of walking based on the human biology, the proposal of walking robot model and its mathematical description.

This walk is solved as the statically stabile in each instant of movement. The proposal system of robot walking provides the sufficient stability in its movement by the CoG transfer above the individual supporting areas of feet. From this walking analysis we will to develop the new walk's types with respect to optimize and to keep the stability of two-leg robot's step.

Acknowledgements

This contribution is the result of the project implementation: KEGA – 059TUKE-4/2014"Rozvoj kvality života, tvorivosti a motoriky hendikepovaných a starších osôb s podporou robotických zariadení", supported by the Research & Development operational Program funded by the ERDF.

REFERENCES

[1] BENIAK, JURAJ-KRIŽAN, PETER-MATÚŠ, MILOŠ: *Accuracy of Rapid Prototyped models with using of FDM technology.* Applied Mechanics and Materials, vol. 613; 13th International conference on Industrial, Service and Humanoid Robotics, ROBTEP 2014, Štrbské Pleso, Slovakia, 15-17 May 2014, p. 390–395.

[2] BENIAK, JURAJ-KRIŽAN, PETER-MATÚŠ, MILOŠ-KOVÁČOVÁ, MONIKA: *The operating load of a disintegration machine.* Acta Polytechnica, vol. 54, no. 1 (2014), p. 1–5.

[3] ČIRIP M., HAJDUK M.: *Návrh stabilizácie a matematických modelov kráčania humanoidných robotov*. Písomná práca k dizertačnej skúške, Košice, 2010, p. 47.

[4] GOLA A., KONCZAL W.: *RMS – system of the future or new trend in science?,* Advances in Science and Technology, vol. 7, no. 20, 2013, p. 35–41.

[5] GOLA A., SOBASZEK Ł.: *Implementation of MS Access software for casing-class manufacturing features saving,* Applied Computer Science, vol. 10, no. 2, 2014, p. 44–56.

[6] HAJDUK M., MARKO Ľ.: *Prístupy k navrhovaniu a riadenia exoskelotonu*. Písomná práca k dizertačnej skúške, Košice, 2010, p. 47.

[7] JONG HWAN KIM, PRAHLAD V.: *Trends in Intelligent robotics: 13th FIRA Robot World Congress,* FIRA 2010 Bangalore, India, September 15-17, 2010 Proceedings, Springer Berlin Heidelberg, New York 2010.

[8] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning*. Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[9] NEMEC M.: *Návrh bipedálneho kráčajúceho podvozku servisného robota*. Doktorandská dizertačná práca, KVTaR, SjF TUKE, Košice 2005.

[10] OLARU A.: *Virtual LabVIEW instrumentation in the technical research of the robots elements and the systéme.* Bren P Publishing, Bucharest, 2002.

[11] RISTIĆ D: *RoboWalker Mobile Robot – Assisted Gait Rehabilitation System*, Durrant 2010.

Jarosław Zubrzycki[1], Katarzyna Piotrowska[1]

RESEARCHES OVER THE DURABILITY ENLARGEMENT OF SWORD-BLADE SAW APPLIED TO THE CUT OF CONVEYOR BELT THROUGH PLATTING LAYERS FROM TITANIUM NITRIDE (TIN)

1. INTRODUCTION

Problems with the effective cut of, armored steel cords are known for years and did not find till the present moment practically satisfying (with the attention on costs or the efficiency of the cut) solution, especially in underground mines, in this about the considerable degree of the methane danger explosion. With the attention on folded structure and use, conveyors belts are the quite dangerous and difficult technical object to utilization. The exploited conveyors belts creates the large danger both for working nearby workers how and for the different machines which use her. One of the simplest and the most effective removing methods of the used belt is her cuts up on smaller pieces, which don't inflict larger difficulties in haulage them from the place of the cut to the forwarding shaft and then on the surface. With attention on this, that the average length of the forwarding belt e.g. the belt conveyor this minimum hundreds of meters, that has why amount of necessary slits is so many large, that the durability improvement of sword-blade saw designed to the tapes cut is the essential to the solution question.

The factors which making difficult the cut is here, among others, the structure of belt and materials combinations used to her production (Fig. 1).

[1] Lublin University of Technology, Institute of Technological Systems of Information, Nadbystrzycka Str. 36, 20-618, Lublin, Poland

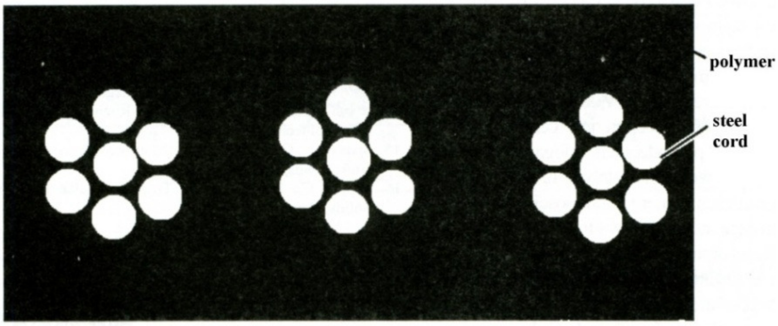


Fig. 1. The section of typical conveyor belt armored steel cords [source: own study]

The considerable width of tape in relation to her thickness, difference in the stiffness of the steel wires of cord and polymer making up the basic constructional material of the tape, can cause the difficulties in the behavior of the required stiffness of fixing (especially steel cords) during the cutting. The tight buildings of the cords by polymer cleading, can in the real way make difficult heat abstraction from the cut zone during cutting off the cords.

2. PLOTTING ON BLADES TOOLS HARD PVD LAYERS ABOUT THE LARGE RESISTANCE ON THE ABRASION

The effective way of enlarging the durability of tools is plotting on their blades the hard layers. I this aim the most often is applied the PVD method (Physical Vapour Deposition), consisting on physical settling thin layers from gas phase. The got layer about the thickness usually grade about 3 ÷ 5 μm possessing very large hardness about 2000 ÷ 3000 HV, considerably enlarges the resistance the tools blades on the abrasive wear. Plotting on the blades of the tools of hard PVD layers, gives the row of the advantage, thanks to which one gets:

- enlargement of the tools durability and their resistance on catastrophic ominous damages (obliteration, crumbles up, breaking off),
- the growth of the efficiency of the processing (in this first of all the cutting off speed),
- improvement of tribological propriety and the hardness of the blade surface,
- improvement of the quality of the processed surface.

Several methods of plotting hard layers comply contemporarily. One of them is Reacting Arc Ion Plating. Thanks to this method is possible to receiving layers about even structure and very good connection with the background, what is very profitable for the new structure. In this method the coat gets thanks to use of three cathodes melted the electric arc. This plotting hard layers makes possible or on large parts, or on the larger number of small parts. Method this allows to plot hard simple and multiple coats. One can also execute many-layered coats both in the micro- how and nano-scale. Rapid tool speed and sintered carbides can be applied as backgrounds, but plotting hard layers on ceramic materials possible is also. The typical kinds of coats made were passed the described method in the table 1.

Tab.1. The typical kinds of PVD coats [source: own study]

Simple	Multicomponents	Multilayers
TiN	(TiAlV)N	TiN/ZrN
ZrN	Ti-Zr-N	TiN/(TiAl)N

3. AIM AND COURSE RESEARCHES

The aim of investigations, was the test of enlargement the durability the sword-blade saws, the HSS and HSS-SL kind , applied to the cut of conveyor belts (fig. 1), armored the steel cords, through plotting protective layers in the figure of the titanium nitride (TiN). For studied tapes, cords endurance was R_m = 1570 MPa, what answers the hardness about 44,6HRC (PN-93/H04357). Testing of the cut of tapes saws covered and without the covering, it was conducted “on dry”, i.e. without the cooling on equipment [3,4]. TiN covered were made in Tools Workshop of WSK PZL Świdnik, in specialist installation applied to the plotting remembered layers.

4. METALLOGRAPHIC RESEARCHES

Investigations of six sword-blades made from rapid tool steel were conducted. Sword-blades were marked suitable numbers. The measurements of hardness were executed the Rockwell method. Additionally were conducted the metallographic macro- and microscopic researches. Sword-blades subjected metallographic researches were characterizing the occurrence of the used zone and zones which did not take the part in the cut (“new”). The sword-blades of no. 1-4 they were covered the layer of the NiT, sword-blades 5 and 6 painted (not covered). Growth of the hardness of sword-blades 5 and 6 can be the result of the larger work temperature in used part (table 1) than the temperature in which they were tempering at the producer what probably called out more far release of the alloying additions carbides. Larger hardness in the waste zone can happened as result of HSS "selfhardening" in the temperature of surroundings, after previous saw warming in the result of intensive thermal processes in the cutting off zone.

4.1. The results of the chosen sword-blades microstructure observation

Sword-blade no. 1 – in non waste zone – rather large, but the disposed the distribution of primary carbides correctly (evenly) and correct emission of secondary carbides. Groundmass – martensite about large spines and retained austenite. In superficial zone related structure, but about different shade on microscopic picture – probably diffusion effect during the cover plotting. In the waste zone the carbides are partially disposed on the former austenite crystallite boundary. In whole capacity clearly banding of structure in parallel direction to surface of sword-blade (fig. 2).

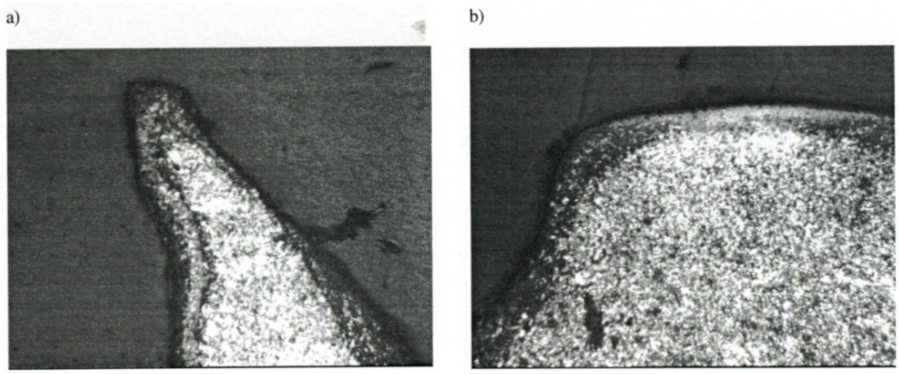


Fig. 2. The sword-blade no. 1: a) the tooth vertex in the sow part which not take the part in cutting off, b) the tooth vertex in the waste sow part (in the top part reject the carbides) [source: own study]

Sword-blade no. 1 – the structure more fine-grained and also the banding. In waste zone blackout nearby the surface. Sword-blade no. 5 – tiny structure without banding, the small predisposition to disposing the carbides on the former austenite crystallite boundary (fig. 3). Sword-blade no 6 – fine-grained structure with predisposition to occur the bands.

How can one notice, from all sword-blades are characteristic the similar structural build sight and almost identical the waste symptoms. One can generally affirm that HSS sword-blade characterized more tiny structure with smaller martensite spines, it's means better than HSS-SL. From the quoted examples of the waste it results that waste leading to the curve of the blade overweighs. From the quoted the waste examples follows that prevail the waste which lead to the rounding of the blade. The absence is the tendency to tearing out or breaking off the teeth (what could be expect taking under the attention the work conditions of the sword-blades, i.e. hand, different feed, cutting off the rope strand, etc.). The generally overweighs rather the material "flowing", and now the waste of the thermal type arise in the result the of admissible temperatures crossing of the work of the blade material.

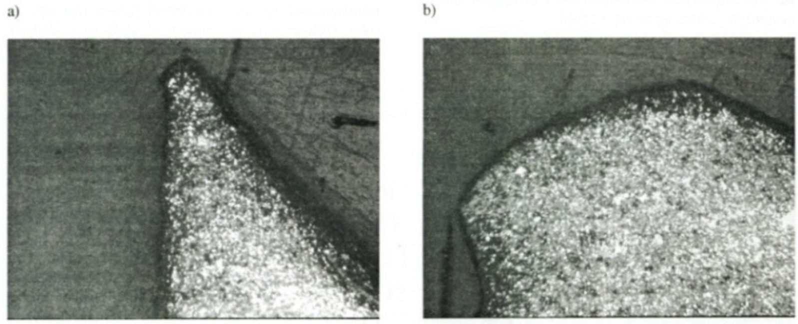


Fig. 3. The sword-blade no. 5: a) the verte of the new tooth, b) and the waste tooth (zoom 100x) [source: own study]

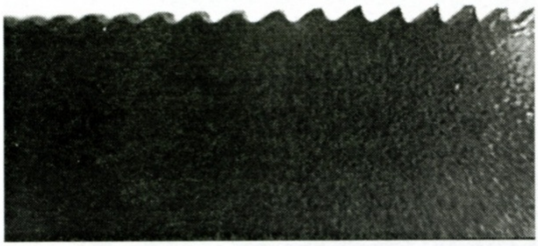


Fig. 4. View of the sword-blade no. 1 fragment in the waste and new part [source: own study]

5. THE RESULTS ANALYSIS

During the station researches affirmed, that both for plotted and not plotted saws theirs dulling occur already after single passing thorough the tape about 160 cm the width, practically past single passing, lasting ca. 7,5 minutes (for both kind of saws). The waste of the saws was so huge, that eliminate them from the more far using. What is the most important, not affirmed the real durability enlargement examined plotted sword-blades.

Having on the attention accomplished observations while duration of the cut process as also the results of metallographic investigations, arises the presumption, that in extreme difficult cutting off conditions, e.g. such as intensive blade frictions about the gum in the cutting off zone, bad heat abstraction from the cutting off zone, the relatively large cutting off speed, average 40m/min (max. even 80m/min, what result from saw construction and power supply parameters), the large hardness of rope steel cords, the lack of forced cooling, the waste of plotted and not plotted saws followed violently and in very short time, a lot of smaller than single belt cut cycle. In such case, by the longer cutting cycle time, the cut was already made blunted saws. And possible differences in time of cycle duration, and value of feed force (not directly measured), were less significant and difficult to noticing.

The problem of the keeping of the constructional materials durability in raised temperatures is very folded, and no to end explained (e.g. [2]). And how shows many researches (e.g. fig. 5), for the HSS steel blades, theirs durability period is strongly depended from cutting off speed.

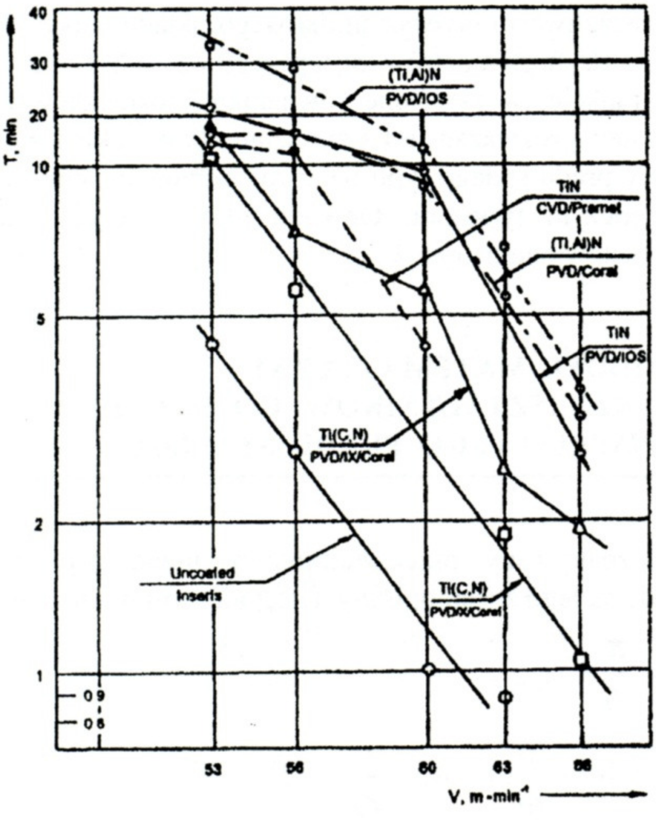


Fig. 5. The influence of the cutting off speed and kind of covering on durability the blades from high-speed steel according to [1] [source: own study]

In the conditions of researches e.g. [1], period this was not overmuch large. It was oscillated in borders 4 minutes for not platted blades, and 10 minutes for platted blades. For introduced researches, those times could be considerably shorter (with the attention on difficult the work circumstances of saws and elemental blades) and many shorter than time of one passage. Therefore also remembered possibility of operating blunted saw by the most part of the cut cycle and the lack of measurable effects. However to decide these matters, more detailed researches indispensable are.

Should also turn the attention, that the results of researches quoted in numerous publications, concern the blades about completely different construction and different sizes. There are considered blades made from HSS steel plates (various kind), mainly from definite sintered carbides, which posses considerable larger length of cutting edges, thickness, heat capacity etc, different like in case of studied blades. Besides, thermal weight studied saws blades could be considerable larger than remembered cutting off plates, used in cutting off tools of the type like turning knives and face milling cutter. And finally, achieved saws durability could be accordingly lower.

6. CONCLUSIONS

Conducted researches doesn't given acceptable answer in processed theme. It could be arise from many reasons, in this from limited range of researches. Agitate subject is very folded and, rather, shouldn't wait simple answers.

One can suppose, that the immediately clear improvement of saws durability can give use the cooling agent radically reducing the friction in cutting off zone, e.g. the suitably well-chosen water solution of the "Ludwik" liquid. One should however conduct appropriate tests. Eventually, one would belong conducted wider tests over adaptation multilayer covers, which in the various researches, in hard cutting off conditions gives larger assurance to get required durability of blade (for sintered carbides plates). The costs can however prove the problem, and so and the advisability of applying this solution.

REFERENCES

[1] MUSIALEK K.: *Pofetsku-FHtp.* IOS Report, DS95-2 7.4. Kraków 1997.

[2] WEROŃSKI A., HEJWOWSKI T.: *Problematyka trwałości elementów pracujących przy podwyższonych temperaturach.* Wyd. Pol. Lub. 1993.

[3] *Piła brzeszczotowa pneumatyczna, typ 5 1213.* Katalog - Biuro Techniczno- Handlowe „Mechanizacja", Katowice.

[4] *Przyrząd do ciecia taśm transportowych.* Wzór użytkowy BTH Mechanizacja w Katowicach.

[5] GODSE R. V., SANTHANAM A.T.: *Composite CVD+PVD coatings.* Materials Science and Engineering A209 (1996), Elsevier, p. 384–388.

Peter Tuleja[1]

ECOLOGICAL ASPECTS OF THE COMPRESSED AIR ENERGY SAVING

1. INTRODUCTION

In assessing the operating costs of automated production may be missing energy balance calculation [1,4,7]. Today, the calculation regarded as one of the key issues [5,6].

If we model the automated production construed as input-output system, figure 1, the input consists of three basic parameters: the material basis of production (material), information base and working energy.

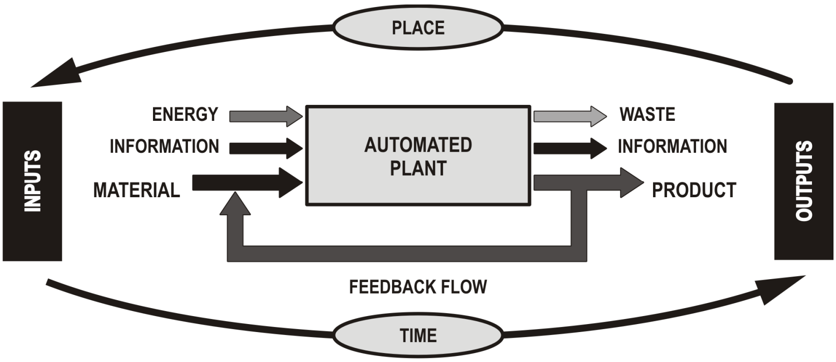


Fig. 1. Model of automated manufacturing [source: own study]

The energy entering the manufacturing process is not the utilization of absolute and arises a so called energy waste [2,8,9]. This fact is in most cases necessary and given the current level of technological options unsolvable. However, if the saving part of the input energy, decreasing the amount of energy waste.

[1] Technická Univerzita v Košiciach, Strojnícka fakulta, Katedra robotiky, Nemcovej 32, 042 00 Košice, e-mail: peter.tuleja@tuke.sk

The energy balance of each production system is closely related to the energy economy of each country [10,12,13]. However, since the globalization of the world refers to the energy sector, the impact on the environment of the earth is the same worldwide. Each MWh acquired production of basic (primary) sources of energy (especially electricity) is a new burden on the Earth's atmosphere tons of emissions. According to some sources or renewable energy sources in this area are not completely "without sin". Ecological approach is therefore be brought into production balancing as an integral part [11].

Total world production and consumption of energy gradually increases, Fig. 2, which necessarily represents a direct impact on the environment. The main types of energy saving in production processes thus reducing the direct impact of the production human activities on the environment.

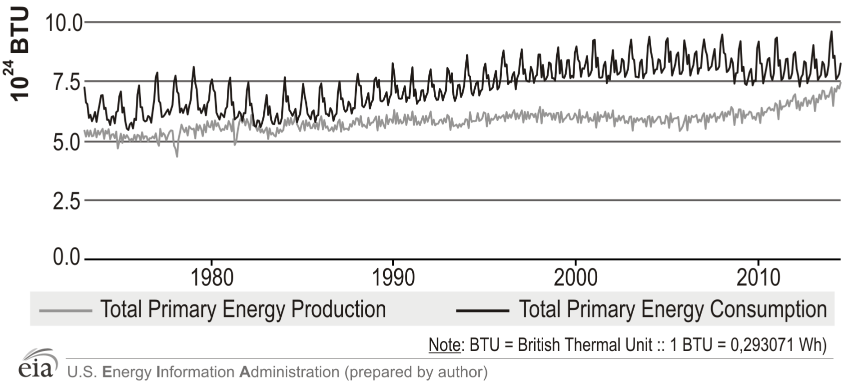


Fig. 2. Evolution of the total consumption of the basic forms of energy in the world [source: U.S. Energy Information Administration]

In automated plants for electricity is widely used energy of compressed air. Since the compressed air produced in compressors powered by electricity, the savings can be realized even in saving compressed air.

2. ENERGY CONSUMPTION IN AUTOMATED PRODUCTION

Kyoto Conference on Climate Change (December 1997) brought about a shift in the understanding of ecological approaches in the management of energy in the manufacturing sector. In an effort to stop global warming began each industrialized countries to consider the real reduction of the share of emissions atmosphere burdensome primary or secondary industrial activity of man (6% reduction in CO_2 emissions in the period 1990-2010).

CO_2 emissions are closely linked to the production of electricity, which the compressed air system consumes up to 20% of total world consumption Fig. 3 a).

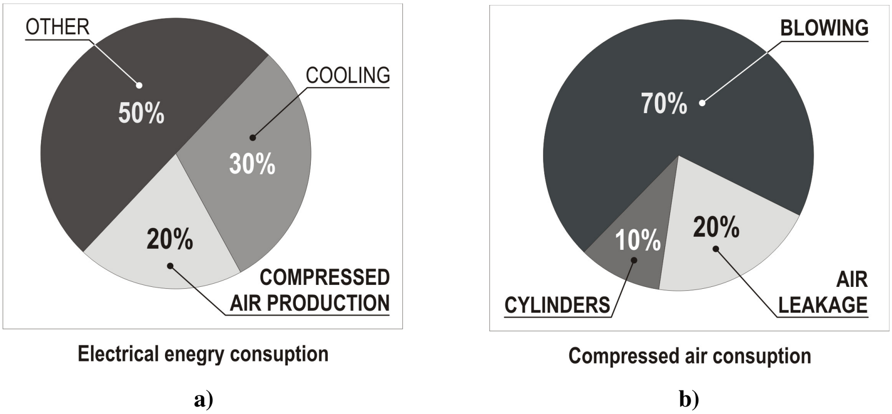


Fig. 3. The percentage of electricity consumption for production of compressed air and its area of greatest consumption [7, 8]

The amount of input costs for compressed air operation more expensive compressed air devices (as compared to the use of other energy). That is why in this area to achieve substantial savings. However, it is to know where and under what conditions is the best saving of.

In general, each inefficiently consumed m^3 of compressed air creates operational loss of production.

3. RULES FOR SAVING COMPRESSED AIR

Statistics indicate that the total consumption of compressed air operating companies up to 20% are losses incurred by leakage of compressed air from the pneumatic circuits and distribution mechanisms, 70% is the volume of compressed air used for various forms of blowing (blowing chips during cutting, drying of coat-ings and the like and for supplying the vacuum jet generators (ejectors), Fig. 3b).

Thus, the saving in the field of release of wide scale intervention in the circuit, leading to a saving of compressed air and thus to primary energy savings.

When the project of divorce the compressed air in operation must be complied with the following conditions:

- internal diameter pipe (effective area) optimized with respect to an application flow needs;
- ensure absolute tightness of connections;
- air pressure maintain at a level which is essential for the operation;
- location of fittings in the divorce must be handled with respect to their ease of maintainability (replacement, inspection, repair, leak detection).

Any leaks in joints or the damaged lines, compressed air and pneumatic circuits in themselves mechanisms induce significant increase in operating costs, Tab. 1.

Tab. 1. The financial statement of losses due to leakage in the circuit [1, 2]

Bore diameter (total leakage)		**Volume of leaked air** [mn^3/min] pri tlaku 0,6 MPa	**The annual cost to at a price 0,04 €/m^3** and operation of the 6000 hours/year
Ø [mm]	**Corresponding area** [mm^2]		
1	0,786	0,06	864.- €
3	7,069	0,55	7 920.- €
5	19,635	1,52	21 888.- €
10	78,540	6,10	87 840.- €

Checking the tightness of joints shall be pay due regard. The first check is carried out after the realization of a first pressurization of system before starting the machinery (without air consumption). Following the pressure loss per hour. This information provides us peace leakage circuit after assembly.

Consequently, it must be made sealing detected leakage (eg. using special leak of compressed air detectors, Fig. 4) and the test repeated.

Fig. 4. Ultrasonic device for leak of compressed air measuring CTRL UL101 (CTRL Systems, Inc., Canada)

When tightness of divorce conforms, the test is repeated after the expiry of such one month. If the air consumption has increased since the last measurement, the system was any leakage of one of the joints (or more) and it is necessary a re-sealing. Similarly, the leakage test carried out on themselves pneumatic mechanisms.

This process is relatively lengthy and requires some degree experience, therefore leading producers of pneumatic components come with developed systems for energy saving (Energy Saving Systems).

Them on the basis of knowledge of options for savings in air consumption seek to improve customer awareness of energy saving (awareness of the costs).

All systems operate with an input condition concerning the recognition of the need to carry out the circuit changes, resulting in the improvement in the state.

However, this presupposes have the relevant data on the actual performance of air consumption at individual workplaces, Fig. 5.

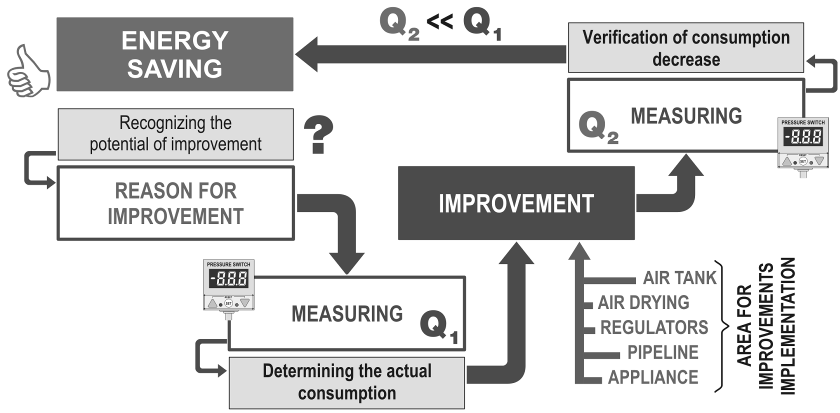


Fig. 5. Procedure for the application of the system for energy saving [7, 8]

Fig. 6. Digital pressure sensor/switch ZSE40A (SMC Corp., Japan)

Fig. 7. The flowmeter PF3W (SMC Corp., Japan)

If the process to be successful, it is necessary to have suitable measuring apparatus for detecting the two basic parameters of pneumatic circuit: pressure, Fig. 6 and the flow rate, Fig. 7.

In other words, at the beginning and at the end of the implementation of axles that can reduce the cost of production of the compressed air line it must be measured.

It is necessary to identify the place where, in what quantities and for what purpose the energy used (determination of reasonableness rate of consumption).

Improving the efficiency of energy saving can be implemented only with sufficient knowledge and control the flow and energy consumption; improve the overall outcome expressed in numerical values should be sufficiently convincing for each user.

4. CONCLUSIONS

The sustainability of economic growth requires reducing the cost of implementation and operation of automated workplaces.

Cost is strongly influenced by the amount of operating costs, which counts the preparation and distribution of compressed air in operation.

If the industry does not attempt to reduce these costs, grow basic energy consumption (especially electricity) and not necessarily result in an increase in emissions in the atmosphere of our planet.

Therefore, an extensive system of growth necessarily need to replace its intense form, because of the risk that the factory will produce products for mankind a dying as a result of environmental disasters.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multirobotic systems".

REFERENCES

[1] GOLA A., MONTUSIEWICZ J., ŚWIĆ A.: *Computer Aided FMS machine tools subsystem selection using the Evolutionary System of Multicriteria Analysis.* Applied Computer Science, vol. 7, no. 1, 2011, p. 18–29.

[2] HAJDUK, M., TULEJA, P.: *Výroba, úprava a rozvodstlačeného vzduchu a vákua.* Základy pneumatických mechanizmov I, TU v Košiciach, Košice, 2013.

[3] Kol.: SMC Training, *Stlačený vzduch a jeho využití,* SMC Industrial Automation CZ, Brno2002/2007, (firemná literatúra).

[4] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A., *A predictive model of multi-stage production planning.* Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.

[5] OPIELAK K., KASNER R., PIASECKA I., SIEKIERKA Ł. TOMPOROWSKI A.: *Mehrschneiden-zerkleinerung der polymer-laminate – teil 2: experimentale forschungen*. Ekologia i Technika, vol. XXII, no. 6, 2014, p. 364–370.
[6] OPIELAK K., KASNER R., PIASECKA I., SIEKIERKA Ł. TOMPOROWSKI A.: *Mehrschneiden-Zerkleinerung der Polymer-Laminate – Teil 1: mathematisches model.* Ekologia i Technika, vol. XXII, no. 6, 2014, p. 359–363.
[7] ŚWIĆ A., GOLA A., WOŁOS D.: *A Method for Increasing the Economical Effectiveness of the Low Rigidity Shafts Machining Process*, Actual Problems of Economics, no. 11(161) 2014, p. 469–477.
[8] http://www.ctrlsys.com/library/downloads/Datasheet%20UL101.pdf
[9] http://www.eia.gov
[10] http://www.smc.sk
[11] http://www.smceu.com
[12] https://content2.smcetech.com/pdf/PF3W-C_EU.pdf
[13] https://content2.smcetech.com/pdf/ZSE40A-ISE40A-A_EU.pdf

Jan Semjon[1]

SERVICE METHODOLOGY FOR THE DESIGN OF MULTIROBOTICS ASSEMBLY SYSTEMS

1. BASIC PARTS OF WELDING FIXTURES

Welding fixtures are peripheral devices of robotized workplace, see figure 1, determined to accurate positioning of welded parts toward to robot. It's controlled by control system of robot or superior system [2,4]. Welding fixture of robotized workplace should have attached fixed or through suitable type of positioner equipped with holder for fixture with one or more axes. Due to this is possible to attach better accessibility to welding points [5].

Basic parts of welding fixtures include:

- basic frames, plates,
- horizontal and vertical structural elements,
- locating elements,
- clamping equipment,
- connecting elements, consoles,
- sensor, energy distribution.

Variety of products requires also various solutions of fixture [1]. This variety raises high requirement to flexibility of fixture i.e. fast pre – sorting to new type of weld. Constructional arrangement of welding fixtures depends from many factors. Important includes: number, size and weight of welded parts, type of used robot – work envelope, type of welding (spot, arc, laser), speed of welding, tact of workplace, method of inserting and removing welded parts, financial possibilities and etc. [7]

Common problem with proposal of modular fixtures is designing of basic concept type and dimensional type for individual parts of fixture. Approach to this solution is based on modular principle i.e. determination of dimensional line at individual parts of fixtures and method their fast connection and disconnection in their mutual compatibility.

[1] Technical University of Kosice, Faculty of Mechanical Engineering, Department of Robotic, Letna 9, 04200, Košice, Slovakia, e-mail: jan.semjon@tuke.sk

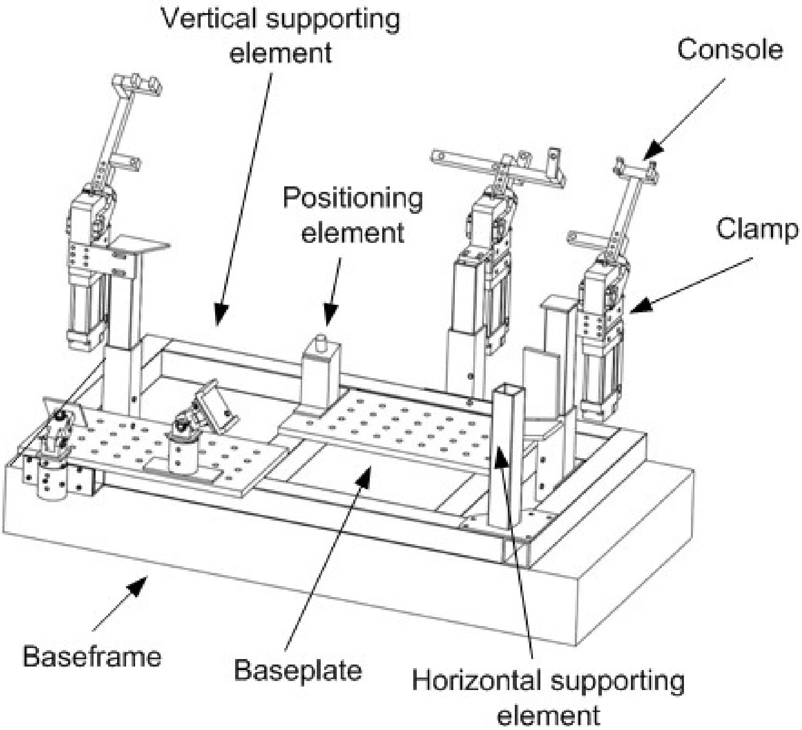


Fig. 1. Model of welding fixture [source: own study]

2. SERVICE METHODOLOGY FOR ROBOTIZED ASSEMBLY CELLS

Proposal succession of welding fixtures for robotized workplace, figure 2 is developed from basic requirement, including:

- shape of welded parts – dimensions,
- material of welded parts,
- process of their mutual connection to resultant assembly,
- method of inserting and removing parts,
- tact of manufacturing,
- type of welding method, dimensions and technological parameters of spot welding pliers (welding tongs),
- type and keeping method of necessary energy distribution (air supply, electricity, suction, etc.),
- security requirements to operation, methods of approaches to operators and maintenance for fixture.

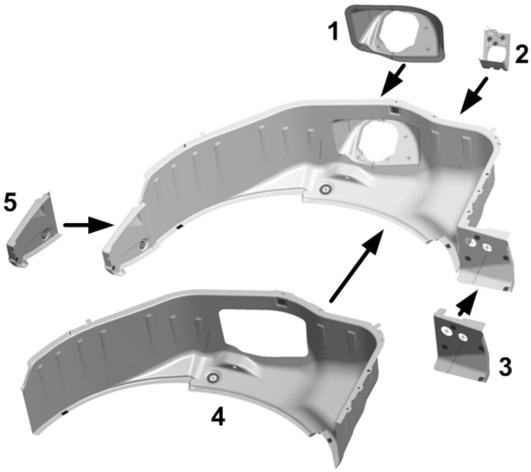
Based on analysis of boundary criteria is for proposal of welding fixture possible to determine following steps [6]:

- determining of mutual position of parts and determining process their inserting,
- choice from database modules, preliminary conception of fixture in 3D,
- choice of locating and clamp points,
- testing availability of robot to welded points (places),
- constructional design of fixture,
- creating of program for robot through off-line programming in simulation program due to testing of accession to welds and also due to monitoring of collision status,
- debugging of program directly at real robotized workplace.

Determination of mutual position parts and determination of sequence their inserting (Position of parts in fixture) – Based on the individual input parameters of welded components and technological sequence are determined succession (steps) of their placing, positioning and orientation in space before welding, figure 2. The output from this analysis is definition of the dimensional characteristics of the fixture (maximal length, minimal height of welded parts etc.) like also selection suitable approach of end effector to welded parts.

Selection of location and clamping points (Selection of location and clamping points (surfaces)) – In this step, preliminary are determined possible points or surfaces for the setting and positioning and their shape as well, see figure 3. Further, determined are also the possible clamping points, necessary clamping force (surfaces) and possible positions of the clamps, sensors and energy.

Selection of individual modules from database (Modules selection, preliminary proposal of fixture – Outputs from the first and second step define the requirements placed on the selection of the individual modules of fixture. The selection is created from the formed database of the individual modules applying the interactive method. Chosen modules must be mutually compatibility and also must be secured through suitable links and relations. The result is a set of the suitable modules, which can be used for constructing of fixture. Next step is calculating respectively selection of necessary clamping forces, which holds part in defined position without surface damage. Based on tests realized at sheets used in automotive industry is possible to say, that clamping force grows at least twice near to increasing of sheet thickness about 0,5 mm (in case of distance putting at two support each other about value 200 mm).



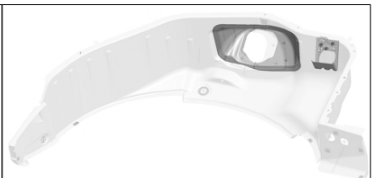
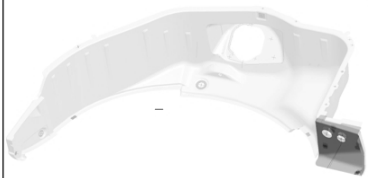
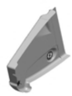
1. STEP: insertion of of parts 1 and 2 situated on the back of weldments	1 2 	
2. STEP: insertion of part 3 located on the right side of the weldment	3 	
3. STEP: insertion of part 4 of the middle of weldment	4 	
4. STEP: insertion of part 5 located on the left side of the weldment	5 	

Fig. 2. Sequence of connecting individual parts at welded assembly [source: own study]

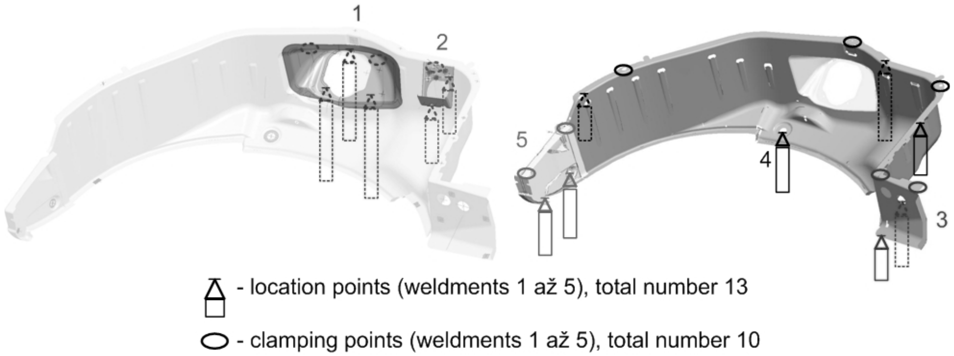


Fig. 3. Selection of location and clamping points [source: own study]

Design assembly of fixture (Constructional design of fixture) – Design of the assembly of the fixture is conducted in CAD system applying 3D modeling and when selected the modules, decision is made based on the mutual dimensional and functional compatibility. The assembly of the fixture is in this step tested with the objective to assume requested accuracy, in 3D is tested the accessibility to the welded points and determined are the possible positions of welding tongs or determined is their optimum position. Figure 4 shows a view at designed welding fixture before inserting of welding parts. There are placed points of weld n. 1 and 2, clamping consoles of welds n. 3 and n. 4 and pneumatic clamps to adherence of welds n. 5 and n. 6.

Fixtures with consoles are placed in opened status due to simply inserting parts. Also must be maintained correct sequence of inserting individual parts (from welds n. 1 till n. 5).

Figure 5 shows a view to designed welding fixture. There are shown all welding parts in correct position held by consoles which is placed on pneumatic fixtures. In this point of proposal for welding fixture suitable at robotized welding is possible verification and test functionality of fixture. For verification of functionality welding fixture is suitable to check some basic points, especially [3]:

- correct location of welding parts – checking their position at space,
- stability of individual parts in fixture, quality location of individual parts,
- accessibility of welding pliers (welding torch) to welding positions,
- correct down force of individual consoles in point for connection with weld, contact force of fixtures,
- simply inserting of individual parts and simply removing done weld.

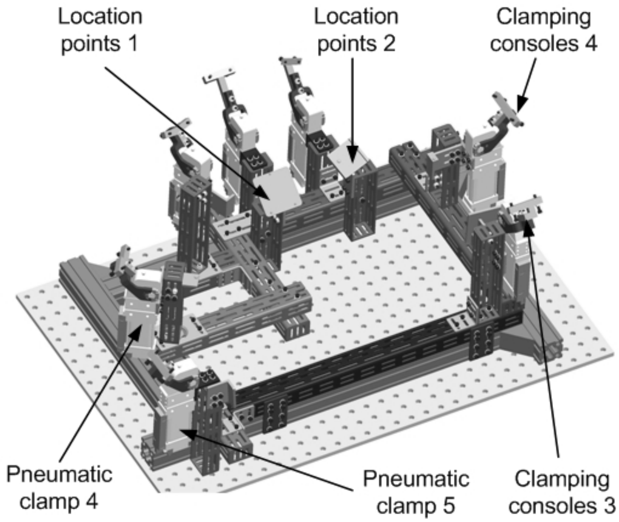


Fig. 4. Assembly of welding fixture without welding parts [source: own study]

In consideration of previous requirements follows checking all parameters of robot and end effector. The checking of dead position at robot arms and maximum movements of all axes is checked on 3D model of robot. In necessary case is chosen and designed suitable base under robot. All this steps are necessary for achievement of suitable robot accessibility to all points for welding. In last step is defined a base position of robot at space because this is the way to simply and safe inserting and removing all of welding parts.

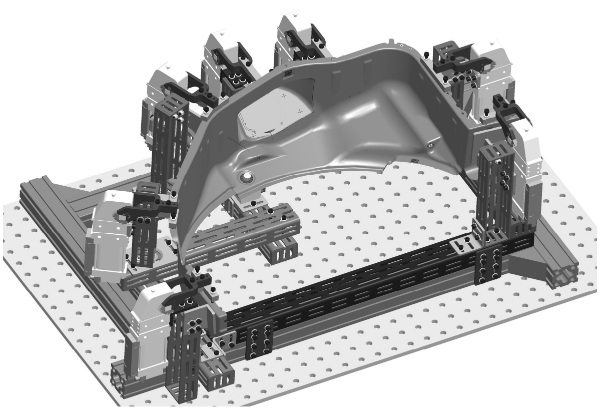


Fig. 5. The assembly of welding fixture prepared for welding [source: own study]

Off-line preparing of program for robot (Off-line programming, generating of program for robot) – If all previous requirements are preserved is possible access to creating of program for robot. The program of robot can be created at any simulating program – environment, which must by compatible with chosen robot and must preserved work with imported folders. Within this environment as RobCAD, ABB Robot studio and similar is possible to path simulation of all robot axis, testing of collision relationships, and also movements optimizing for decreasing of secondary times [8].

Debugging of robot program on real workplace (Debugging of program at workplace) – Generated program is inserted to control system of robot, where continues its ongoing testing and debugging, figure 8. Operator of robot – workplace, in necessary case fine tunes movements of robot directly on real workplace and supervises accessibility, accuracy and quality of welding. In case of hardly repairable error must operator of robot analyzed reasons and applies suitable countermeasures.

3. CONCLUSIONS

The target of paper was to design a methodology for modular welding fixture, which is suitable for using in automotive industry. The fixture must accomplish requirements of modularity. This is important for reconfigurable and remodel from one type of fixture to another for simply and time-saving at operators. Next aim at proposal of modular welding fixture is ability to simplify a design process for welding fixtures to designers. This leads to an effective usage of designer’s work as well as to decrease of costs at fixture manufacturing.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11 “Principles of profiling and cooperation multirobotic systems”.

REFERENCES

[1] BENIAK J., KRIŽAN P., MATÚŠ M.: *Accuracy of Rapid Prototyped models with using of FDM technology*. In: Applied Mechanics and Materials, vol. 613, 2014, p. 390–395.

[2] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems’ Evolution from the Flexiblity Level Point of View*. [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[3] HAJDUK M., SEMJON J., VAGAS M.: *Design of the welding fixture for the robotic station for spot welding based on the modular concept*, Acta Mechanica Slovaca, vol. 4, 2009, p. 30–36, ISSN 1335-2393.

[4] KOZŁOWSKI E., TERKAJ W., GOLA A., HAJDUK M., ŚWIĆ A.: *A predictive model of multi-stage production planning*. Management and Production Review, vol. 5, no. 3, 2014, p. 23–32.
[5] SEMJON J. et al.: *Modular Welding Fixtures for Robotic Cells*. Applied Mechanics and Materials, vol. 309, 2013, p. 80–87.
[6] SEMJON J., HAJDUK M.: *Zváracie prípravky robotizovaného pracoviska*, Strojárstvo. Vol. 12, 2012, p. 110–112.
[7] ŚWIĆ A., GOLA A.: *Economic Analysis of Casing Parts Production in a Flexible Manufacturing System*. Actual Problems of Economics, no. 3 (141) 2013, pp. 526-533.
[8] VAGAS M. et al.: *The view to the current state of robotics*. Advanced Materials – Research, vol. 463–464, 2012, p. 1711–1714.

Antoni Świć[1], Arkadiusz Gola[2], Victor Taranenko[3]

DYNAMIC SYSTEM MODELING OF SHAFT MACHINING PROCESS IN ELASTIC DEFORMABLE CONDITION

1. INTRODUCTION

Continued efforts aimed at obtaining high-quality machining on machine tools under conditions of various interferences affecting the technological system (TS) have led to the application of adaptive control (AC) systems in the machine-building industry [4,11,12]. The problem of improvement of such systems is particularly relevant under ESP conditions, in the realization of so-called "no-man" technology [2,5]. Development of a mathematical model (MM) of control object (CO) in the dynamics, adequate to the original object, is a prerequisite for substantiated approach to the solution of the problem of analysis of stability of automatic control systems (ACS) or AC and synthesis of correcting elements, in accordance with required quality indices of transition process control. Whereas, in similar systems, indexes of quality of control of the input variable – elastic deformation in the dynamic TS - characterize directly the errors of shape of the machined parts, determined by the effect of rapidly changing interferences of the type of change in material allowance for machining or variability of the physicochemical properties of the machined material [10,14].

The dynamic system (DS) of the process of machining is a technological system, i.e. a machine tool together with the realized technological process (TP) of machining (turning, grinding, drilling, milling) [7,13].

Systemic analysis, as the basis for analysis and synthesis of ACS and AC, is based on the assumption that the specifics of the assumed objects and processes results not only from the properties of the component elements, but is determined by the character of their mutual relationships that have a decisive effect on the structure of the ACS or AC.

[1] Lublin University of Technology, Institute of Technological Systems of Information, Nadbystrzycka Str. 36, 20-618, Lublin, Poland
[2] Lublin University of Technology, Department of Enterprise Organization, Nadbystrzycka Str. 38, 20-618, Lublin, Poland
[3] Lutsk National Technical University, 75 Lvivska str., c. Lutsk, Volyn reg., 43018, Ukraine

In the identification of DS the systemic approach includes the following fundamental stages [13]:

- analysis of input data for identification;
- formulation of control strategy oriented at a specific subsystem of basic machine tools, in accordance with input data in designing ACS, AC;
- exclusion of invariant, relative to their spectrum, input effects of subsystems and components within the limits of technical capability of ACS, AC and the machine tools;
- analysis of possible structures of *MM* of control system with respect to their function, types of components and connections between them, number of levels of hierarchy, principles of connection, and permanence of the connections.

With a lack of sufficiently complete and detailed information on the object of control, calculated characteristics may significantly differ from the true ones. The parameters (settings) of regulators adopted in design do not guarantee the required quality of control, or even stability of the system. Apart from this, the analysed systems are characterized by extensive variability of parameters of the CO. Those determinations indicate the complexity of the problem of ensuring stability of the ACS and the necessity of taking special care in the approach to the problem of defining its structure and synthesis of the corrective devices.

2. IDENTIFICATION OF DYNAMIC SYSTEMS OF SHAFT TURNING

In the case when there is complete information on the object of control it is possible to design a model using the analytical method. Such a procedure, leading to the identification of the structure and parameters of a model, is referred to as analytical identification. For complex systems, development of MM with the analytical method frequently requires additional experimental tests aimed at the verification of theoretical results and at determination of some of the model parameters.

The possibility of linearization of equations of motion of the particular components of the DS follows also from the commonly accepted view that assurance of high requirements with respect to precision of adjustment is reduced to realization of adjustment systems operating at “small” deviations of variables. Therefore, the dynamic system of the process of drilling can be considered as multi-dimensional CO with subsystems in the form of the technological process and an elastic system. The structure of the CO includes circuits of feedbacks from the elastic system caused by force effects that appear in the course of realization of the technological process.

References [8,9,13] present a system of equations and a generalized structural schematic of MM of the dynamic system of shaft turning. The developed system of equations and the structural schematic of MM take into account the geometry of the machined layer and of the machining force in turning, elastic properties of the TS, process of forming of cross-section of the machined layer (ML). The process of forming of cross-section of the ML takes into account the phenomenon of machining “following the feed ridge” which consists in that the components of the machined layer of the material at the current moment are defined by the temporary position of the cutting edge and by its coordinates at the moment of the preceding revolution of the semi-finished product, i.e. at a time-lag of a single revolution. At the same time the effect of elastic deformation for coordinate Z on the depth of turning is taken into account.

The process of forming of the cross-section of ML is under strong effect of the phenomenon of machining “following the feed ridge” and by elastic deformations in the DS. The process of forming of ML cross-section can be described with a system of integral-differential equations with delayed argument. Variables characterizing the ML cross-section depend on the input variables and on the elastic deformation in the DS. In the vector of the technological variables, formed by the dynamic system, two components can be distinguished – one defined by the vector of input effects and the other by the vector of elastic deformations.

Elements of the vector of input values are the control values in the form of the straight feed rate, rotational speed of the machined part, and also interference in the form of changes in the hardness of the machined material and in the machining allowance relative to the length and diameter of the machined part. The vector of elastic deformations is determined by the vectors of machining forces and of control values entering the system of vibrational stability assurance. Dynamic properties of the equivalent elastic system can be approximated with quadratic equations [1]. The choice of the vector of technological variables is significantly affected by the phenomenon of machining “following the feed ridge”, manifest in that the momentary values of the components of the said vector are determined by the values of elements of the input vector and of the vector of elastic deformations not only at the current moment but also at the time of the preceding revolution of the machined part. Due to this, the dynamic system is described with a system of integral-differential equations with variable delayed argument.

As a result of analysis of the processes occurring in the dynamic system of machining, a system of equations and functions of transition were obtained, as well as the generalized structure of the control object.

3. IDENTIFICATION OF DS OF TURNING OF LOW-RIGIDITY SHAFTS

To improve the precision of machining of shafts with low rigidity, technological methods were developed for the control of machining precision, based on change in the elastic-deformable condition [16,17]. As control effects, in accordance with the developed classification [15], particular force control effects are employed, or their combinations – axial and eccentric tension, control by means of additional force effects aimed at compensation of force factors from the machining process, bending moments at supports, control of force-induced bending-torsional strain.

MM of various technological systems of machining with control of the elastic-deformable status for stabilised parameters, presented in the form of deflection functions, were obtained with the assumption that a bending force acting on the machined part is an external variable that is independent of the elastic deformations in the DS. This approach is based on not including the closing of the elastic system through the process of machining and does not introduce new errors into results of analyses of static characteristics of the CO. Analysis of the structure of a suitable MM of a control object for transition parameters is not possible without taking into consideration the specifics of processes within the machining zone and the closing of the DS through the process of machining.

MM of the considered control object – DS with control of the elastic-deformable status of parts with low rigidity was constructed on the basis of general principles of creating MM of DS [3,8,13] of machining, with the specifics of the process of machining of parts with low rigidity being accounted for by the introduction of suitable equations of constraints [6,13], reflecting mutual relationships between additional elastic deformations Δg_{ξ}, into one of the equations representing the force control effects of the system of equations. Equivalent elastic deformations of the *TS* in the machining of parts with low rigidity can be represented in the form of two components:

$$g_{\zeta} = g_{\zeta obr.} + g_{\zeta cz.} \tag{1}$$

where: $g_{\zeta obr.}$ and $g_{\zeta cz.}$ – elastic deformations of the machine tool, fixture, tool and part for each coordinate, respectively; $\zeta \in \{x, y, z\}$. The first component in this expression for the TS under consideration is, in principle, lower by one order of magnitude and can be neglected.

Elastic deformations of the TS in the radial direction g_y in accordance with the deflection equations [16], at set parameters without the inclusion of closed status of the CO, may be considered as a deterministic non-linear function of the part parameters L, d, EI; components of the machining force F_c, F_p, F_f; coordinates x of machining force application on the length of the semi-finished product and various regulatory effects in the form of: tensile force F_{x1}; eccentric tensile force creating two regulatory effects F_{x1} and moment $M = F_{x1} \cdot e$, where e – eccentric of the tensile forces; one or more additional forces $F_{dod.i}$; bending moments M_i; torsional moment M_{skr}, or their combinations:

$$g = f(L, d, EI, F_c, F_p, F_f, F_{x1}, e, F_{dod.i}, M_i, M_{skr}, x) \tag{2}$$

Assuming that the true feed rate and the rate of change of coordinate x are relatively small, in the analysis of transition processes the change in coordinate x in the function of time can be left out. Therefore, relation (2) in the operator form can be written as:

$$\begin{aligned} g_y(s) &= K_{xy} \cdot F_f(s) + K_{yy} \cdot F_p(s) + K_{zy} \cdot F_c(s) + K_{F_{x1}} \cdot F_{x1}(s) + \\ &+ K_e \cdot e(s) + K_{F_{dod.i}} \cdot F_{dod.i}(s) + K_{M_i} \cdot M_i(s) + K_{M_{skr}} \cdot M_{skr}(s) \end{aligned} \tag{3}$$

where: dual indexes at coefficients K mean that coefficients K_{xy}, K_{zy} indicate the effect of increase in the values of components F_f, F_c on increase in the level of elastic strain on coordinate y; $K_e = K_e^{'} \cdot F_{x1_0}$. The gain coefficients of linear equations are defined as fragmentary derivatives of the strain function along the respective coordinate. For example, for the TS of machining with the effect of axial tensile force F_{x1}, causing elastic-deformable condition, from the system of elastic deformations we obtain [13]:

$$K_{yy} = \left(\frac{\partial g_y}{\partial F_p} \right)_0 = \frac{L^3 \cdot [1 - \cos(2\pi x_0 / L)]^2}{2\pi^2 \cdot (4\pi^2 \cdot EI + F_{x1_0} \cdot L^2)} \tag{4}$$

$$K_{F_{x1}} = \left(\frac{\partial g_y}{\partial F_{x1}} \right)_0 = -\frac{F_p \cdot L^5 [1 - \cos(2\pi x_0 / L)]^2}{2\pi^2 \cdot (4\pi^2 \cdot EI + F_{x1} \cdot L^2)} = -\frac{g_{y_0} \cdot L^2}{4\pi^2 \cdot EI + F_{x1} \cdot L^2} \tag{5}$$

where: F_{x1_0}, g_{y_0} – values of tensile force and elastic strain of the part along coordinate y at the point of linearisation (values of variables relative to which increases of variables are given).

In the special case under consideration the remaining coefficients in relation (3) are equal to zero. Coefficients of gain, corresponding to different DS at various methods of loading (i.e. with axial-radial bending and various methods of fixing) in machining of elastic-deformable parts, obtained in an analogous manner, are presented in [13,17] – x_0 – coordinate of cutting edge position on machining length at the point of linearisation. The additional elastic strains g_x, g_z with respect to coordinates x and z, as a result of the action of the control force effects under consideration, basically do not have any significant effect on the dynamic properties of the CO and can be treated as negligible.

In accordance with the result of studies in ref. [16], the components of machining force without inclusion of the contact strain at the surface of application are written as:

$$F_c = Q_{pw} \cdot a \cdot b\,, \quad F_p = Q_{pw} \cdot a \cdot b \cdot K'_y\,, \quad F_f = Q_{pw} \cdot a \cdot b \cdot K'_x\,,$$

where: Q_{pw} – relative work of formation of shaving, K'_y, K'_x – constant coefficients for given conditions of machining.

Hence

$$m_z = \left(\frac{\partial F_c}{\partial a}\right)_0 = Q_{pw_0} \cdot b_0 \cdot K_z\ ,\ m_y = \left(\frac{\partial F_p}{\partial a}\right)_0 = Q_{pw_0} \cdot b_0 \cdot K_y\ ,$$

$$m_x = \left(\frac{\partial F_f}{\partial a}\right)_0 = Q_{pw_0} \cdot b_0 \cdot K_x\ ,$$

$$n_z = \left(\frac{\partial F_c}{\partial b}\right)_0 = Q_{pw_0} \cdot a_0 \cdot K_z\,,\ n_y = \left(\frac{\partial F_p}{\partial b}\right)_0 = Q_{pw_0} \cdot a_0 \cdot K_y\ ,$$

$$n_x = \left(\frac{\partial F_f}{\partial b}\right)_0 = Q_{pw_0} \cdot a_0 \cdot K_x$$

and

$$n_y m_x = Q_{pw_0} a_0 K_y Q_{pw_0} b_0 K_x\ , \quad m_z n_x = Q_{pw_0} b_0 K_z Q_{pw_0} a_0 K_x\ ,$$

$$m_y n_x = Q_{pw_0} b_0 K_y Q_{pw_0} a_0 K_x\ , \quad n_z m_x = Q_{pw_0} a_0 K_z Q_{pw_0} b_0 K_x\ ,$$

$$n_y m_x = m_y n_x\ , \quad m_z n_x = n_z m_x\ .$$

The relations given above permit simple transformations of coefficients A and B included in corresponding operator transmittances (OT) of the CO with relation to various control and interfering effects.

In referenced works [13,17] the authors analysed the possibility of replacing the obtained relations of OT with approximated ones, application of which significantly simplifies calculation of characteristics of DS MM. The analysis was made according to the criterion of recreation of true characteristics of MM with approximated relations in the time and frequency planes; it was demonstrated that the form of approximating relations should be chosen taking into account the numerical value of coefficient B. It was also determined that the value of $B = 0{,}1$ is the "limit" at which the switch from one form of approximating relation to another is justified. The value of coefficient B is defined as the ratio of rigidity of equivalent elastic system to gain coefficients of the process of machining and can be adopted as an index of relative rigidity of DS. Broad ranges of variability of machining parameters on machine tools, e.g. of change in the hardness of the machined material, machining allowance, cutting edge geometry, determine broad ranges of variability of coefficients $m_x, m_y, K_{\kappa_r}, K_x, K_{yy}$ and B, respectively.

Calculations show that in machining of low-rigidity shafts and in roughing and profiling of parts with normal rigidity the values of coefficient B are notably greater than the limit value of $B = 0{,}1$; in this case also the approximating relations for OT according to (11), (14), (15) should be built by splitting the exponential function $e^{-s\tau}$ into a Pade series which, keeping the first two components, may be written as:

$$e^{-s\tau} = \left(1 - \frac{1}{2}s \cdot \tau + \frac{1}{12}s^2 \cdot \tau^2\right) / \left(1 + \frac{1}{2}s \cdot \tau + \frac{1}{12}s^2 \cdot \tau^2\right) \tag{6}$$

In the case of control of the elastic-deformable condition of parts with low rigidity through the application of tensile force F_{x1} the structure of CO has been developed in [13,17].

On the basis of the schematic given in [13,17], after transformation, the relation for OT of the dynamic system when increase in elastic deformations g_y in the radial direction is adopted as the initial variable is reduced to the form of:

$$G_{F_{x1}}(s) = \frac{g_y(s)}{F_{x1}(s)} = K_0 \cdot \frac{1 + A' \cdot (1 - e^{-s\tau})}{1 + B' \cdot (1 - e^{-s\tau})} \tag{7}$$

where:

$$K_0 = K_{F_{x1}} \cdot \frac{1}{1 + K_{yy} \cdot n_y + K_{xy} \cdot n_x + K_{bz} \cdot K_z \cdot n_z} \tag{8}$$

$$A' = m_x \cdot K_x + K_{\kappa_r} \cdot m_y \cdot K_y \tag{9}$$

$$B' = \frac{m_x \cdot K_x + K_{\kappa_r} \cdot m_y \cdot K_{yy} \left\lfloor 2 + K_{yy} \cdot n_y + K_{bz} \cdot n_z + K_{xy} \cdot m_x / (K_{yy} \cdot m_y) + K_{bz} \cdot K_z \cdot m_z / (K_{yy} \cdot m_y) \right\rfloor}{1 + K_{yy} \cdot n_y + K_{xy} \cdot n_x + K_{bz} \cdot K_z \cdot n_z} \tag{10}$$

For known values of coefficients included in relations (7)–(10), the relations can be notably simplified. Calculations show that in machining of parts with low rigidity with application of force effects components containing K_{bz} and K_{xy} can be basically left out. In such a situation, the relation for B' gets considerably simplified, and the expression for coefficients K_0 is notably reduced. Denominator of OT of operator transmittance for DS determined from the relation in control of straight feed [8,9] is reduced, as shown above, to the form of denominator of aperiodic component of the first or second order. To transform the numerator of OT to a typical form one can also employ splitting the function $e^{-s\tau}$ into a Pade series, and then the analysed OT will assume the form of:

$$G_{F_{x1}}(s) = K_0 \cdot \frac{T_3^2 \cdot s^2 + T_3' \cdot s + 1}{(T_1 \cdot s + 1) \cdot (T_2 \cdot s + 1)} \tag{11}$$

The time constants T_1 and T_2 are determined from the relation:

$$T_{1,2} = 0{,}5\tau \cdot \left[0{,}5 + B \pm \sqrt{(0{,}5 + B)^2 - 1/3} \right] \tag{12}$$

by substituting in it B' to replace B, and the time constants in the numerator are then equal to:

$$T_3 = 0{,}289\tau; T_3' = (0{,}5 + A') \cdot \tau \tag{13}$$

4. SIMPLIFICATION OF DYNAMIC SYSTEM MM OF SHAFT TURNING IN ELASTIC-DEFORMABLE CONDITION

Further transformations of the numerator of OT (7) should be made with the inclusion of time constants T_3 and T_3' which depend on A'. If $A' < 0{,}077$, then the OT of UD can be written in the following typical form:

$$G_{F_{x1}}(s) = \frac{g_y(s)}{F_{x1}(s)} = K_0 \cdot \frac{T_3^2 \cdot s^2 + 2\varepsilon \cdot T_3 \cdot s + 1}{(T_1 \cdot s + 1) \cdot (T_2 \cdot s + 1)} \tag{14}$$

where: ε – coefficient of attenuation:

$$\varepsilon = \frac{0{,}5 + A'}{0{,}577} \tag{15}$$

In the case when $A' \geq 0{,}078$, the approximating relation for the analysed OT assumes the form of:

$$G_{F_{x1}} = \frac{g_y(s)}{F_{x1}(s)} = K_0 \cdot \frac{(T_4 \cdot s + 1) \cdot (T_5 \cdot s + 1)}{(T_1 \cdot s + 1) \cdot (T_2 \cdot s + 1)} \tag{16}$$

where:

$$T_{4,5} = 0{,}5\tau \cdot \left[0{,}5 + A' \pm \sqrt{(0{,}5 + A')^2 - 1/3} \right]$$

In an analogous way, on the basis of the generalized structural schematic and system of equations models of DS were obtained for other control effects. The approximating relations of dynamic system OT for various control effects differ from those presented here only in the value of the gain coefficient K_0 of the CO. Instead of coefficient $K_{F_{x1}}$ in relation (8) for K_0, in such a case coefficients of gain for the respective effects $K_e, K_{F_{dod.i}}, K_{M_i}, K_{M_{skr.}}$ are inserted. The values of those coefficients can be calculated according to the relations given in [13].

In many cases, with accuracy sufficient for practical engineering calculations, approximating relations for OT (7) should be built with the use of the first component of the splitting of function $e^{-s\tau}$ into a Pade series:

$$e^{-s\tau} = (1 - \frac{1}{2} s \cdot \tau)/(1 + \frac{1}{2} s \cdot \tau) \tag{17}$$

5. EXPERIMENTAL RESEARCH ON DS CHARACTERISTICS

The aim of the experimental research on TS dynamical characteristics during elastic-deformable parts turning consist in estimation of adequacy the object MM (obtained basing on analytical methods of identification) to the original.

During testing the object interactions on test reactions, it is necessary to define self inertia of the system's executive element – pneumatic drive. Analysis of the pneumatic element's equation of motion informs that its dynamic properties can be approximately described by aperiodic link of OT [8]:

$$G_{np}(s) = \frac{K_n}{T_n s + 1}$$

where the equivalent time-constant T_n is equal to *0,01-0,02s* – it depends on initial air-powered cylinder piston position.

The authors presented the initial coordinate of the object, in which they considered the gain in elastic strains by coordinate *Y*, giving the input elementary pitch signal which takes into consideration the executive element inertia. The operational transmittance is equal to

$$\Delta g_y(s) = \frac{1}{s} G_n(s) G_{Fg_y}(s) = \frac{K_n K_{0Fg_y}(T_{05}s+1)(T_{06}s+1)}{s(T_n s+1)(T_{01}s+1)(T_{02}s+1)}$$

The research carried out shows that time-constants in numerator and denominator of OT object have similar value and their dynamic properties are related to properties of proportional link; that is why the transient process by giving the element input pitch is defined mostly by its element properties. For example, by experimental research of time characteristics, the machining process of a steel 45 part with diameter of 5 mm and length of 200 mm was carried out. The machining parameters were: $a=0.2mm$; $b_1=0.75mm$; $\kappa_r=90°$; $v_c=0.3m/s$; $\tau=0.047s$, the initial value of tensile force was $F_{x1}=1980N$.

According to references [8,9], the defined values of factors m_x, m_y were: $m_x=m_y=0,61\cdot 10^6 N/m$. The coefficients of elastic system reaction by coordinate *X* were, in that case, defined mostly by machine tool elastic properties and $h_{xx}=3\cdot 10^{-7} m/N$ and by coordinate *Y* – by the elastic properties of the part. Calculations were carried out according to relations mentioned in [3,8], for a case when cutting force is applied in the middle point of the part: initial value of the part elastic strains was $g_{y0}=0,11\cdot 10^{-3} m$, $h_{yy}=1,2\cdot 10^{-6} m/N$. The values of factors B_0 and B were: $B_0=0,18$, $B=0,17$.

Taking into consideration that values of B_0 and B are close, the object can be considered, in approximation, as proportional link and transient characteristic – defined by executive element inertia. Actually, the experiment results show that curve of the transient process has, in that conditions, an exponential course with time constant T_{np}.

6. SYNTHESIS OF P CONTROLLER

The problem of optimal control of TS elastic-deformable condition is computed analogous to the one considered in [15,17]. Besides, it is unnecessary to correct the system parameters settings, thanks to quite high stability of the control system parameters. The control system properties are similar to proportional link parameters, according to the results mentioned above. In lots of cases, interferential reaction (in the form of machining allowance change) can be considered as normal stationary random process and the random correlations function of the interferences coordinate can be approximated by exponential-cosines relation:

$$K(\tau) = D \cdot e^{-\alpha\tau} \cos \beta\tau \tag{18}$$

where: D – dispersion of the random process, α – index of correlation function decay, β – frequency of correlation function change.

On equal terms with mathematical model of interferences in the form of random process with correlation function (18), the random process of "white noise" type can be considered as the interferential model. The model of "white noise" type as the border case of not correlated process is advised to be applied when there is no credible information of random process characteristics. It should be taken into consideration that deviation Δg is considered here as regulated coordinate.

Choosing the proper start of Δg mean value computing, that factor can be reduced to zero. Therefore, the interference is going to be considered as a random process with mathematical expectation equal to zero.

In the capacity of optimisation criterion for TSs, which are exposed to interferences in the stationery random process form, it is suitable to take into consideration the minimum of mean value of deviation square Δg^2 with restrictions on the driving power u^2 and to describe that criterion in following form:

$$\mathrm{J} = m^2 < \Delta g^2 > + < u^2 > \tag{19}$$

where: m – indefinite Lagrange multiplier.

The operational transmittance (when the generalized object factor refers to the controller and the proportional link is the dynamic object model) is equal to:

$$G_o(s) = \frac{B_o(s)}{A_o(s)} = 1$$

We synthesize the optimum controller (according to criterion (19)) for interference in the form of random process with exponential-cosines function (18). Standard spectral interference power density is

$$S_\varphi(\omega) = \frac{\alpha^2 + \beta^2 + \omega^2}{(\alpha^2 + \beta^2 + \omega^2)^2 - 4\beta^2\omega^2}$$

and can be defined in the following form (after presenting by Laplace and separating):

$$S_\varphi(s) = S_1(s) S_1(-s)$$

where:

$$S_1(s) = \frac{b_{s0}s + b_{s1}}{a_{s0}s^2 + a_{s1}s + a_{s2}}$$

$$S_1(-s) = \frac{b_{s0}s + b_{s1}}{a_{s0}s^2 - a_{s1}s + a_{s2}}$$

We can write down the multi-nominal expression, applying the methodology of synthesis:

$$G(s)G(-s) = A_o(s)A_o(-s) + m^2 = 1 + m^2$$

$$G(s) = G(-s) = \sqrt{1 + m^2}$$

Indirect expression for considered case is:

$$\frac{A_o(-s)}{G(-s)}S_1(s) = \frac{1}{\sqrt{1+m^2}} \cdot \frac{b_{s0}s + b_{s1}}{a_{s0}s^2 + a_{s1}s + a_{s2}}$$

Its total part equals zero, because the order of magnitude for the denominator multi-nominal is higher than the numerator multi-nominal and the denominator multi-nominal of that expression has no solution in the left half-plane, therefore:

$$M_0(s) = 0, M_-(s) = 0$$

$$M_+(s) = \frac{1}{\sqrt{1+m^2}} \cdot \frac{b_{s0}s + b_{s1}}{a_{s0}s^2 + a_{s1}s + a_{s2}}$$

There is an expression for auxiliary function:

$$\Phi(s) = \frac{M_+(s)}{G(s)S_1(s)} = \frac{1}{1+m^2}$$

and the operational transmittance of optimum controller is equal to:

$$G_r(s) = A_o(s) - \frac{1}{\Phi(s)} = -m^2$$

Hence, similarly to the case of interference in the form of random process with exponential-cosines function, the optimum controller is a typical proportional controller and its proportionality coefficient is described by selected level of limitations on the control reaction.

Similar to the previous description, it is easy to obtain expressions for OT of closed system by interference and control, expressions that become proportionality coefficients and, after transition to frequency plane, they become expressions for square of amplitude frequency characteristic relative to the control and interfering reaction.

Taken into consideration the obtained correlations, the mean square deviation of initial coordinate Δg^2 and mean square value of the control reaction Δu^2 are defined.

7. CONCLUSIONS

As follows from the performed study, dynamic structures of MM of technological systems for low-rigidity shafts with control of their elastic-deformable condition include, apart from inertial segments characteristic for MM of feed-related control, also overload segments. The occurrence of the overload segments in transmittances of the MM reduces the inertness of the control objects with respect to channels of control of additional force effects. For example, with close values of time constants of the numerator and denominator in relations, as happens is numerous cases, the properties of the model of CO approach those of the non-inertial segment with transmission coefficient K_0.

It should be emphasized that the discussed mathematical description of the *CO* was made with the exclusion of "small" time constants characterising the dynamic properties of the process of machining and of the equivalent elastic system. Such an approach is justified as the *ACS* or *AC* circuit includes, apart from the object, also an automatic control device and other components with "large" time constants, whose dynamic properties are highly significant in the solution of the problem of stability analysis and synthesis of corrective segments.

Comparison of MM of the object for various control effects permits the statement that with the application of additional force effects the object has a notably lower inertness compared to the case of control focused on the feed channel. Thanks to this, in the *ACS* and *AC* of the elastic-deformable condition of parts higher indexes of control quality can be achieved in the dynamics and there is a possibility of effective counteraction of interference caused by changes in material allowance for machining and in the hardness of machined semi-finished products by varying their rigidity on the length of machining.

REFERENCES

[1] ABAKUMOW A., TARANENKO W., ZUBRZYCKI J.: *Program modules for the study of characteristics of the dynamic system of machining process* (in Polish). Zeszyty Naukowe Politechniki Rzeszowskiej NR 230 MECHANIKA, z. 67 – Modułowe Technologie i Konstrukcje w Budowie Maszyn. Rzeszów 2006, p. 99–109.

[2] FRER F., ORTENBURGER F.: *Vvedenije v elektronnuyu techniku regulirovaniya*. – Moskva: Energiya, 1973, s. 423.
[3] LEVCHENKO A., TARANENKO V.: *Identification and automation of deep-hole drilling*. Preoceedings of The 2nd International Conference On Machining and Measurements of Sculptured Surfaces 20-22 September 2000, Krakow, Poland, p.149–154.
[4] SOLOMENCEV J.M., MITROFANOV V.G., TARANENKO V.A.: *Adaptive control of machine tools* (in Slovak). Bratislava: ALFA, 1983, p. 231.
[5] ŚWIĆ A, TARANENKO W. *Adaptive control of machining accuracy of axial-symmetrical low-rigidity parts in elastic-deformable state.* Eksploatacja i Niezawodność – Maintenance and Reliability 2012, no. 3, vol. 14, p. 215–221.
[6] ŚWIĆ A. *Technologia obróbki wałów o małej sztywności*. Lublin: Wydawnictwo Politechniki Lubelskiej 2009, p. 244.
[7] ŚWIĆ A., GOLA A., WOŁOS D.: *A Method for Increasing the Economical Effectiveness of the Low Rigidity Shafts Machining Process*, Actual Problems of Economics/Актуальні Проблеми Економіки, no. 11(161) 2014, p. 469–477.
[8] ŚWIĆ A., GOLA A.: *A Method of Qualification of Parts for Production in a Flexible Manufacturing System*, Actual Problems of Economics/Актуальні Проблеми Економіки, no. 11 (149) 2013, p. 576–585.
[9] ŚWIĆ A., GOLA A.: *Economic Analysis of Casing Parts Production in a Flexible Manufacturing System,* Actual Problems of Economics/Актуальні Проблеми Економіки, No. 3 (141) 2013, p. 526–533.
[10] ŚWIĆ A., WOŁOS D., LITAK G. *Method of control of machining accuracy of low-rigidity elastic-deformable shafts.* Latin American Journal of Solids and Structures, vol. 11, no. 2 (2014), p. 260–278.
[11] ŚWIĆ A., WOŁOS D., ZUBRZYCKI J., OPIELAK M., GOLA A., TARANENKO V.: *Accuracy Control in the Machining of Low Rigidity Shafts*, Applied Mechanics and Materials, vol. 613, 2014, p. 357–367.
[12] TARANENKO G.,TARANENKO V., SZABELSKI J., SWIC A.: *Systemic analysis of models of dynamic systems of shaft machining in elastic-deformable condition.* Applied Computer Science. Business Process Optimization, vol. 3, no. 2, 2007, Technical University of Żilina, Slovenska Republika, 2007, p. 215–238.
[13] TARANENKO W., ŚWIĆ A.: *Technology of profiling machine parts with low rigidity* (in Polish). Wydawnictwo Politechniki Lubelskiej, Lublin 2005, p. 282.
[14] TARANENKO W., ŚWIĆ A:. *Devices of control of machining precision of machine parts of low rigidity* (in Polish). Wydawnictwo Politechniki Lubelskiej, Lublin 2006, p. 186.
[15] HAJDUK M., JENČÍK P., JEZNÝ J., VARGOVČÍK L.: *Trends in industrial robotics development.* In: Applied Mechanics and Materials, vol. 282, 2013, p. 1–6.
[16] BALÁŽ V., VAGAŠ M., HAJDUK M., SEJMON J.: *Modular Training System in Virtual Reality Environment – MSEVRT*, Applied Computer Science, vol. 9, no. 1, 2013, p. 46–53.
[17] HAJDUK M., VARGA J., DUROVSKY F.: *Optimization and Design of Four Gripper Pneumatical Rubik's Cube Solver,* Applied Computer Science, Vol. 10, No. 3, 2014, p. 57–67.

Peter Tuleja[1]

TECHNICAL RESOURCES FOR ENERGY SAVING OF COMPRESSED AIR IN AUTOMATED OPERATION

1. INTRODUCTION

Compressed air energy used in abundance in automated production plants is the most expensive of the available energies [1,4,5].

The high price of energy is apparent from the form of preparation (production) and air-treatment in practice. Generator efficiency (compressor) and the complexity of adjustments depending on the class of air treatment required for the application intended contributes to the high cost of one side, the fact that each liter of prepared compressed air we used only once (recovery is not possible) [2,7,14].

Therefore, the on-site effort leading producer of pneumatic components offer customers such products, which allow to save this expensive media.

Support this effort indirectly offered by the fact that the energy of compressed air is produced using electricity (the vast majority of compressor works based on electric drive unit) and the closely related eklogický view of the problem.

Tab. 1. Financial expressed the cost of production and treatment of compressed air

Unitary quantity of used the compressed air [**m_n^3/min**] by an average working pressure in the circuit 0.6 MPa	**Yearly cost of producing and preparation at a price 0.04 €/m^3** and operation of the 6000 hours/year
1,00	14 400.- €
5,00	72 000.- €
10,00	144 000.- €
20,00	288 000.- €

[1] Technická univerzita v Košiciach, Strojnícka fakulta, Katedra robotiky, Nemcovej 32, 042 00 Košice, e-mail: peter.tuleja@tuke.sk

As another way to reduce operating costs by using compressed air as the working power does not exist it is necessary to identify areas where the use of better components and better layout and equipment of the circuit could save as much compressed air [3,6,12].

If we consider price for the one cubic meter of the produced and conditioned compressed air (average) 0.04 Euros, operating costs are considerably high, tabel 1.

It should be noted that the costs may decrease with lower demands for quality compressed air, but can grow to astronomical numbers if the requirement for high quality.

From this perspective, the use of higher quality (and thus expensive) components or retrofitting an existing circuit components of the energy-saving compressed air, seem reasonable and affordable.

2. WHERE TO SAVE THE COMPRESSED AIR?

To be able to decide the area in which it is possible to save most of the compressed air, we have an idea where the consumption of what, figure 1.

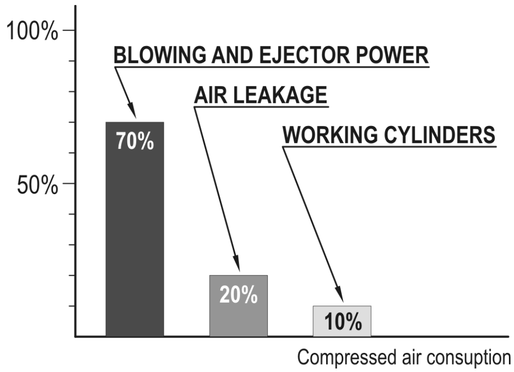


Fig. 1. Percentage air consumption according to its use [9,10]

Firstly, it is necessary to prevent any leakage of compressed air from the circuit. This is true for both the compressed air in the company, and also for the pneumatic circuits at individual workplaces company.

If we can determine the volume of escaping compressed air, see Tab. 1, we know to determine the financial rewards for those losses.

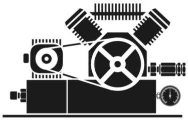
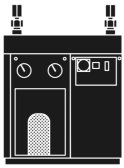
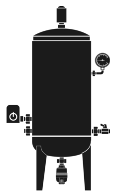
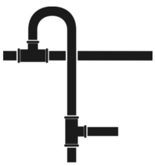
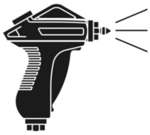
In operation, the pneumatic actuator mechanisms employed in the workplace companies are saving compressed air (in keeping with the principles for their maintenance) possible, but in terms of volumes in many cases, of little interest. (provided that it will not allow leakage losses of the lines and the like).

Most compressed air can be saved especially when used for blowing (whether in technology of machining parts for air blowing, for drying coatings, paint shops, facilities for drying wetted for technological reasons).

Another area of investigation for massive consumption of compressed air supply of vacuum jet generators (ejectors).

Fields of solutions and indicated to the problems referred Tab.2.

Tab. 2. Areas for implementation of axles an effort to energy saving [2, 8, 9]

Area		Tackling the challenge
	**Production of compressed air**	The cost of compressed air. Energy conversion, volumes conversion. Volume conversion of components.
 	**Air drying**	Determination of maximum air flow. Determination of allowable values humidity. Determination of the optimum degree of drying. Selecting an appropriate air cooler. Selecting an appropriate air filter. Selecting an appropriate air dryer.
 	**Pressure control**	Selection of the air tank and stock management. Selection of regulators and multiplicators.
	**Pipelines**	Optimization of system compressed air lines. Determining the rate of loss of pressure in the main pipe. Quantifying the costs associated with leaks. Determining the extent permitted cooling air in the duct.
 	**Air consuming devices**	Determination of air consumption appliances. The selection of suitable components for air blowing. Determination of the required size of the air flow when the optimization averages of lines. Thorough inspection of lines. Optimizing the structure of the pipe.

Consequently, it is necessary to establish a level of saving and inferred proposals for improvements.

Improving the efficiency of energy saving can be implemented only with sufficient knowledge and control the flow and energy consumption; improve the overall outcome expressed in numerical values should be sufficiently convincing for each user.

Implementation of axles is the use of new systems affecting air consumption in key areas of the pneumatic system (Tab. 2).

Furthermore, a software product for recovery options and rates of energy saving individual producers also offer a variety of learning tools on which it is possible to train maintenance staff and operators on the routes in the routine implementation of new products, which have a higher rate of saving energy.

There are several areas of consumption of compressed air, in which the use of new technologies leads to interesting results in the amount of saved compressed air and electricity saved. In particular the device for [11,13]:

- ***control of pressure and/or flow of compressed air*** – monitoring of flow characteristics appropriate electronic flow meters and pressure control switch or by differential digital pressure gauges, Fig. 2;

Fig. 2. Precision digital sensors/pressure switches (SMC) and digital differential manometer (Testo)

- ***control air consumption at time zero consumption –*** technical solutions for the reduction of air leaks on air blowing equipment and cooling at the time of inactivity - eg. due to insufficient sealing leaks blowing guns;
- ***regulation of consumption of compressed air at blowing*** – saving of air when air blowing guns using special types of nozzles with the possibility of obtaining a high value of output current at low input pressure and low air consumption, Fig. 3;
- ***drives of pneumatic tools*** – saving of air designed for pneumatic tools using a special rotary actuators saving air;

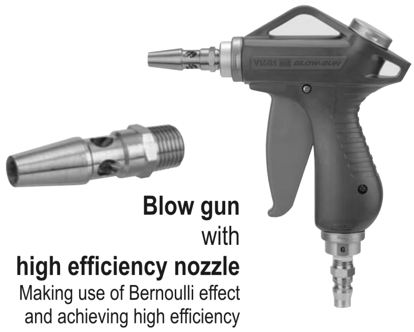


Fig. 3. Blow gun with high efficiency nozzle (SMC)

Fig. 4. Ultrasonic device for leak of compressed air measuring CTRL UL101 (CTRL Systems, Inc., Canada)

- ***monitor leakage of compressed air during its distribution*** – monitoring equipment to detect the location and intensity of air escaping from the manifold, Fig. 4;
- ***ensure minimum pressure drop in the process of adjusting the air*** – using only components strictly necessary to achieve the required purity class of compressed air in relation to an application needs;
- ***saving compressed air in the manufacture of vacuum* –** using a vacuum-saving components;
- ***air transport ensured by the use of process fluids pumps*** – air power saving process pumps in transit coolant, Fig. 5;

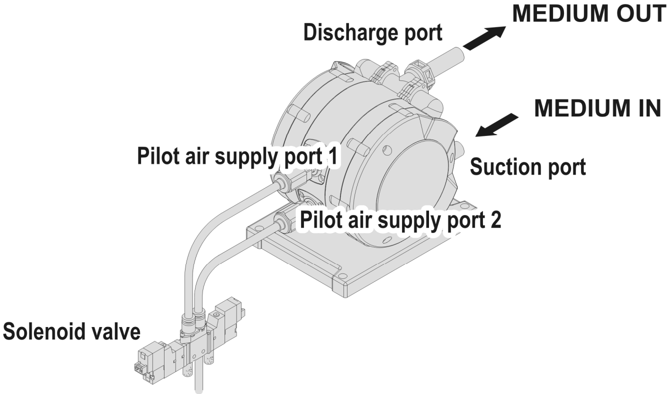


Fig. 5. Process pump controlled by solenoid valve (SMC)

- ***direct reductions in electricity consumption*** – energy savings using indirectly controlled solenoid valves with low power consumption – from 0.15 to 0.35 W and extend lifespan in the right mode of use, Fig. 6.

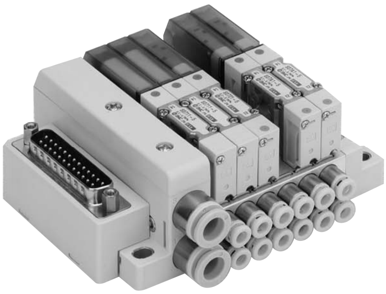


Fig. 6. Valve island with low energy solenoid valves (SMC)

3. CONCLUSIONS

Saving of compressed air in automated plants, on account of the price of compressed air highly desirable. If this issue is not satisfactorily addressed, often leads to serious problems in the financial balance of the operator.

It is important to know the operation that uses compressed air, because only a complete overview of consumption may lead to interest on savings.

Acknowledgements

This contribution is the result of the project implementation: VEGA – 1/0810/11 "Principles of profiling and cooperation multirobotic systems".

REFERENCES

[1] GOLA A., ŚWIĆ A.: *Directions of Manufacturing Systems' Evolution from the Flexiblity Level Point of View*. [in:] Knosala R., Innovations in Management and Production Engineering, Oficyna Wyd. Polskiego Towarzystwa Zarządzania Produkcją, Opole 2012, p. 226–238.

[2] HAJDUK M., TULEJA P.: *Výroba, úprava a rozvod stlačeného vzduchu a vákua.* Základy pneumatických mechanizmov I, TU v Košiciach, Košice, 2013.

[3] Kol.: SMC Training, *Stlačený vzduch a jeho využití,* SMC Industrial Automation CZ, Brno 2002/2007 (firemná literatúra).

[4] OPIELAK K., KASNER R., PIASECKA I., SIEKIERKA Ł. TOMPOROWSKI A.: *Mehrschneiden-Zerkleinerung Der Polymer-Laminate – Teil 2: Experimentale Forschungen*. Ekologia i Technika, vol. XXII, no. 6, 2014, p. 364–370.

[5] OPIELAK K., KASNER R., PIASECKA I., SIEKIERKA Ł. TOMPOROWSKI A.: *Mehrschneiden-Zerkleinerung Der Polymer-Laminate – Teil 1: Mathematisches Model*. Ekologia i Technika, vol. XXII, no. 6, 2014, p. 359–363.

[6] SOBASZEK Ł., GOLA A., ŚWIĆ A.: *Creating Robust Schedules Based on Previous Production Processes,* Actual Problems of Economics, no. 8 (158) 2014, p. 488–495.

[7] ŚWIĆ A., GOLA A.: *A Method of Qualification of Parts for Production in a Flexible Manufacturing System.* Actual Problems of Economics, no. 11 (149) 2013, p. 576–585.

[8] http://www.ctrlsys.com/library/downloads/Datasheet%20UL101.pdf

[9] http://www.smc.sk

[10] http://www.smceu.com

[11] https://content2.smcetech.com/ pdf/VMG-F_EU.pdf

[12] https://content2.smcetech.com/pdf/PAF3000-5000_EU.pdf

[13] https://content2.smcetech.com/pdf/S0700-B_EU.pdf

[14] https://content2.smcetech.com/pdf/ZSE40A-ISE40A-A_EU.pdf

Marian Marek Janczarek[1]

HEAT AND MASS TRANSFER PROCESSES IN THERMAL TREATMENT CHAMBERS FOR FRUIT

1. INTRODUCTION

The main purpose for fruit storage in central European climate is to provide products of high consumption quality during autumn, winter and spring. Financial inputs connected with the maintenance of the storage are obviously related with the final cost of apple or any other fruit. It is necessary to prolong storage period energetically efficiently to maintain affordable price of apple. Contemporary technological processes make possible to inhibit biochemical and physiological processes that lead to ripening or overripe fruit. The prolongation of storage period is mainly achieved by the storage of apple of pear in chambers that can maintain low temperature of fruit, i.e.: within the range between $0 \div +1.5^{o}C$. Beside temperature conditions, it is necessary to provide the air of low oxygen and carbon dioxide contents and of high humidity and circulation in the interior of the cooling chamber. The differences among particular cases of thermal energy demand for storage depends mainly on different construction of cooling chambers. The construction can differ in materials and dimensions which results in different thermal resistance of external walls. Problems of thermal conductivity can be analyzed by many methods, for example: Laplace transformations method, Fourier transforms, etc. The paper presents two models: analog one and differential one. They can help to control heat processes during storage periods.

It has to be noted that building design processes require fluent acquaintance of rules and processes described by building physics also in the aspects of thermal preservation. Buildings should meet requirement related energy savings at simultaneous maintenance of thermal comfort in rooms. Some ignorance of thermal processes occurring in such objects, in particular – insufficient thermal conductivity levels in walls can lead to exaggerated energy losses. This is particularly important because of continuously raising price and increasing pollution of the atmosphere. The parameter that describes wall

[1] Lublin University of Technology, Mechanical Engineering Faculty, ul. Nadbystrzycka 36, PL – 20-618 Lublin, Poland; tel.: +48 81 538 45 82, e-mail: m.janczarek@pollub.pl

thermal conductivity is the coefficient of thermal conductivity $\lambda[Wm^{-1}K^{-1}]$ (k – in some international reference), which is dependent among others on volume density and material structure, water content and temperature. The coefficient of thermal conductivity is the information of energy flux that flows through a unit area of a material layer of 1 m thickness at the temperature difference at both surfaces of this layer equal to 1 K (1°C). The higher the volume density, the higher is the described coefficient and the material transfers heat more easily. Moreover, the materials composed of the same substance can have different coefficients of thermal conductivity when volume density is different. Thermal conductivity can vary in the function of temperature and the heat loss increases at some proportion together with the temperature difference. This phenomenon is the result of complex changes of heat transfer through: conductance in materials which the layer is composed of, convection in fluid components of porous construction and even through heat radiation on internal and external surfaces of the layer. The more porous material is, it causes the lesser heat transfer and through this it prevents heat from the flow outside the structure. Practical implementation of this phenomenon was previously described by the author in extremely low or high temperature i.e.: hot tank insulation. In building envelope the variation of temperature is comparatively small (except for instance – sun exposed dark surface) and the variation of thermal conductance in dependence on temperature can be omitted. It is, however important to provide information of temperature when λ is determined.

The phenomenon of heat transfer through external walls is one of the most important components of heat loss from buildings. This is either important in buildings of constant occupation or in objects of short time use. Thermal conductance of external walls plays a significant role in these losses. The external walls not only protect the building from thermal losses but also influence interior air quality and its humidity. The building envelope should enable, in some extent, the exchange of air and water vapor at simultaneous humidity stabilization. Moreover, one of the most important physical properties qualifying external wall is its thermal capacity – decisive to building thermal stability in the result of thermal inertia. The phenomenon of thermal inertia occurs as a phase shift of heat transfer into the room. Physical properties of wall construction materials undergo disadvantageous changes in the result of dampness which lessens its quality and durability. The efficient protection of building is to avoid negative influence of moisture and to prevent from the following damage. The condition to meet microclimate comfort in rooms is its dry envelope. Damp walls make it impossible even at very intensive heating. Water vapor flow is important in the protection against moisture. Water vapor diffusion through building walls is a process of partial water vapor pressure equalization between two environments divided by the wall. The water vapor flow occurs from the environment of higher concentration to the environment of lower concentration which means that water vapor flows always in the direction of a drier room. The coefficient of vapor transmittance [mg/(m·h·Pa)] characterizes material and structure properties related to vapor diffusion. This coefficient describes the content of water vapor expressed in mg that diffuses through 1 m^2 of a material layer of 1 m thickness during 1 hour and at 1 Pa pressure difference on both sides of this layer. Similarly to the heat transfer through the external building envelope, the diffusive resistance of material layers can be determined, i.e.: $Z = d / \delta$, where d is layer thickness [m]. Water enclosed in pores is of λ equal to 0,56 [$Wm^{-1}K^{-1}$], which is about 20 times the one of air in pore diameter of about 0,05 mm in such material as bricks. Some additional influence on heat transfer is exerted by water vapor diffusion which increases this transfer and by moisture capillary transport. The moisture content increase is followed by some intensification of thermal conduction and among others, that is why thermal insulation gets worse because water gets inside pores instead of the air. This process does not occur identically in different materials and depends on material structure, its origin, e.g. cellular concrete the increase of λ is about 4,5% per 1% moisture content increase.

2. MODELS OF HEAT TRANSFER THROUGH WALL

The purpose of this paper is to describe the design of control systems of cooling and air conditioning systems in storage spaces. For a control systems its necessary to use only three elements: sensor, controller and controlled device. The main of those elements is temperature sensor which shows the picture of thermal decomposition in cold store. The very important are also devices, which provide control of humidity and cyclic potential motion of air in space. It must be noted, that all the control actions depend mainly on measurement of a controlled variable. It is, therefore, necessary to analyze very carefully what is actually being measured, how it may vary with time and which degree of accuracy is necessary in the measurement. Mostly, the temperature of the surfaces on which the sensors are mounted is different from the air temperature.

Conduction take place when a temperature gradient exists in a solid (or stationary fluid) medium. Energy is transferred from the more energetic to the less energetic molecules when neighboring molecules collide. Conductive heat flow occur in the direction of decreasing temperature because higher temperature is associated with higher molecular energy. The equation used to express heat transfer by conduction is known as Fourier’s Law. The article presents the physical model of heat transfer through chamber walls by means of a mathematical model suitable for sine waveform of internal temperature changes.

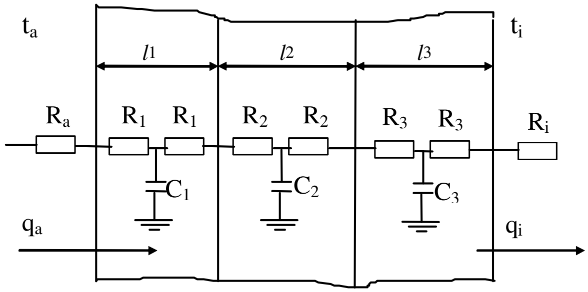


Fig. 1. Model of wall composed of three layers in electrical analogy [source: own study]

From it we can get matrix notation (eventually for n – layers of wall) and the final result of this calculation is a pair of linear relations between the temperature and fluxes at the two surfaces of the composite slabs.

$$[\Delta t_i(p), \Delta q_i(p)] = [\Delta t_a(p); \Delta q_a(p)] \begin{bmatrix} 1 & 0 \\ -R_1 & 1 \end{bmatrix} \begin{bmatrix} 1 & -pC_1 \\ 0 & 1 \end{bmatrix} \cdots \begin{bmatrix} 1 & -pC_n \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -R_{n+1} & 1 \end{bmatrix} \quad (1)$$

The relation is precisely analogous to Ohm's law for the steady flow of electric current: the flux corresponds to the electric current, and the drop of temperature to the drop of potential. Thus R may be called the thermal resistance of the slab. Next suppose we have a composite wall composed of n slabs of different thickness and conductivities. If the slabs are in perfect thermal contact mat their surfaces of separation, the fall of temperature over the whole wall will be the sum of the falls over the component slabs and since the flux is the same at every point, this sum is evidently.

This is equivalent to the statement that the thermal resistance of a composite wall is the sum of the thermal resistance's of the separate layers, assuming perfect thermal contact between them. Finally, consider a composite wall as before, but with contact resistances between the layers such that the flux of heat between the surfaces of consecutive layers is H times the temperature difference between these surfaces. The differential equation to be solved is Fourier's equation.

3. THERMAL RESEARCH ON REAL OBJECT

The verification of the accepted methodology and results have been performed on the data thermal flux density obtained from rural thermal chamber in Radzyń Podlaski (Poland). The small sensor of low inertia has been developed especially for the purpose of the research. This sensor has been used to measure the heat flux density. The experimental analysis proves the necessity to consider the dynamic character of internal temperature when thermal chamber analysis is performed. The thesis includes also the presentation of elaborated methodology of analysis of industrial long term storage.

The purpose for the research is to point out areas subjected to the highest energy loss caused by building construction and geographical orientation of walls. Thermal detectors have been installed on external surfaces, internal surfaces and inside wall layers to measure temperature. The graphical presentation of temperature field distribution on wall surfaces have been performed by means of a thermal vision camera (Fig.3, 4). The camera enables to distinguish visually the areas of the highest thermal loss from storages. The analysis of temperature distribution on vertical walls of storages makes possible to indicate proper building construction of objects. The analysis results are presented in figures. Moreover, temperature measurements taken on chamber external surfaces let us distinguish rooms that serve for other purpose than storage, e.g. a technical room. This room additionally protects the storage from disadvantageous influence of atmospheric conditions.

Article includes analysis of changeable influence in time of variable weather temperature on internal temperature of construction object depending on thermal inertia of building. Taken advantage influence of sinusoidal change external temperature on internal temperature of thermal technical spaces of thermo stability object will allow to get drop of cost of expendable energy of constru-ction object on keeping of definite thermal condition in accommodation properly spaces. It shows harmonist of exemplary characteristic depending on length of time of measurement course of temperature and seasons of the year.

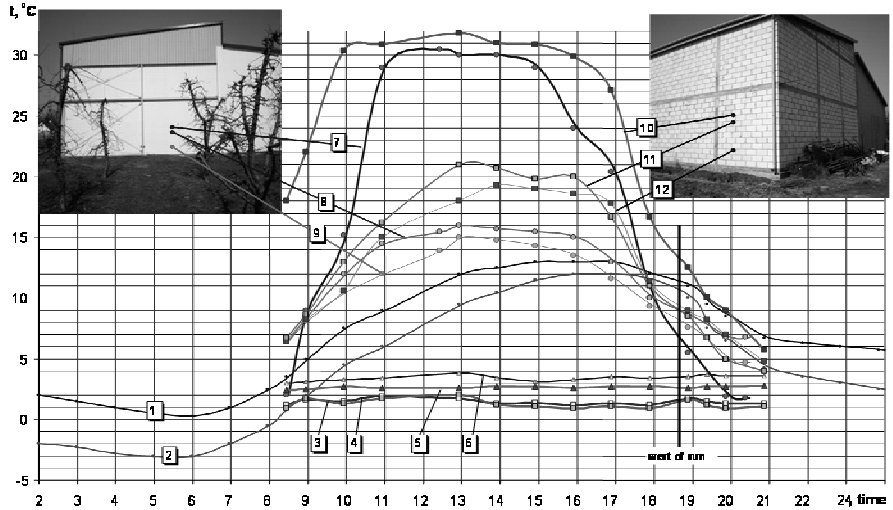


Fig. 2. Presentation of temperature field distribution on wall surfaces [source: own study]

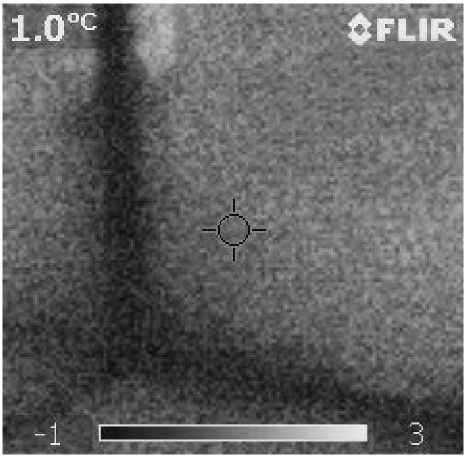


Fig. 3. Temperature field distribution on the corner of wall [source: own study]

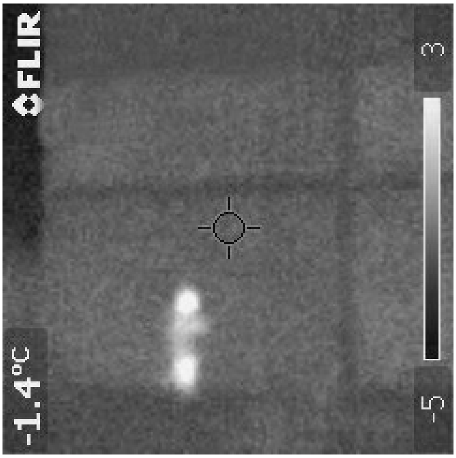


Fig.4. Temperature field distribution on wall surfaces [source: own study]

4. MEASUREMENT POSITION FOR THE RESEARCHING COEFFICIENT OF HEAT TRANSFER IN MATERIALS

In aim of determined of coefficient of heat transfer of bricks in dependences upon of degree her moistures one chose method experimental. Research one passed on laboratory - position in Technical University of Lublin and referred of measurement of temperatures, thickness of streams warm and moistures relative bricks. As material to driven researches used brick full red both wet and then this oneself brick dried in stove. In time of a few days' measurements driven former at a help of computer registration of temperatures in four points on external surfaces examined bricks as also in two central points in interior. Simultaneously driven former computer registration of moisture at help of two searchers of type WHT installed in center of brick. Values of thickness led of warm density became measured at help of electronic sensors of type PTP, which connected former to universal measure APPA.

Position laboratory – to qualifications of coefficient of heat flow in aspect different moistures of equipped brick was in two chambers. Different conditions thermal in chambers held former at help of aggregates cooling and of controlled warmers. Among chambers one installed investigative sample in typical form full red bricks placed tight to capacity in plate of polystyrene about thickness 20 cm. Polystyrene. Plate used former in aim of isolating of surface external bricks from influence undesirable temperatures. Surfaces external bricks surrendered became {remained} to activity from one side of chamber to temperature + 25^0 C and from second side of chamber to temperature + $1{,}5^0$C. Values these of temperatures registered former independently for every from six sensors, and then recorded on disc of computer at measuring – step carrying out 15 of minutes. Simultaneously with measurement of temperature registered former at help of programmed computer values of moisture of brick on two separate files. Obtained from measurements of value of temperatures, of streams and moistures became placed in programmer EXCEL. At the help of suitable mathematical transformations coded values of temperatures and moistures exchanged on suitable individuals on degrees ^{0}C and on per cent definite values of relative moisture.

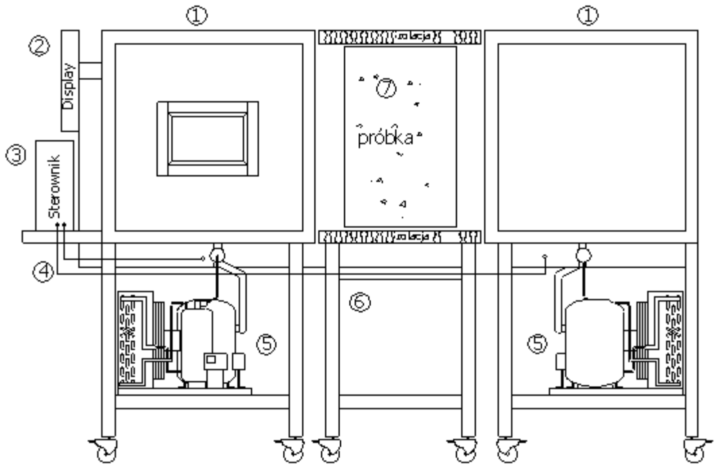


Fig. 5. Schema ideological positions laboratory – to measurement of coefficient of heat transfer [source: own study]

1. Chamber measuring – executed from aluminum - profiles. Thickness of side 10 cm, with full mineral.
2. Display – LCD Samsung SyncMaster about diagonal 15".
3. Driver – computer PC class with operating - system UNIX.
4. Wires driver steering of generative of microclimate in chambers.
5. Laboratory set of Danfoss firm to generating conditions thermal prevalent inside of chambers. Range of temperatures from – 40°C to + 50°C.
6. Table made from aluminum – profiles with variable construction making possible securing and arrangement of prepared samples to investigations.
7. Primary standard sample of builder's material – full red bricks – placed in polystyrene plate.

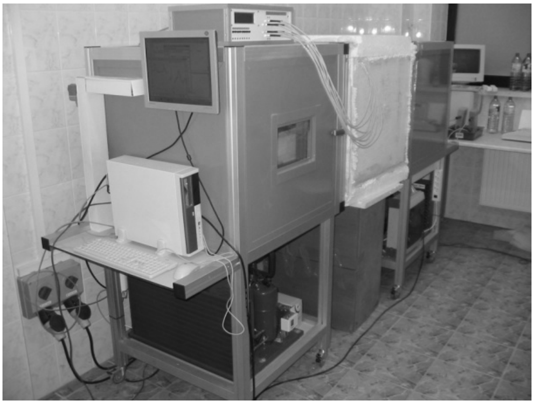


Fig. 6. View general positions laboratory – measuring – chambers [source: own study]

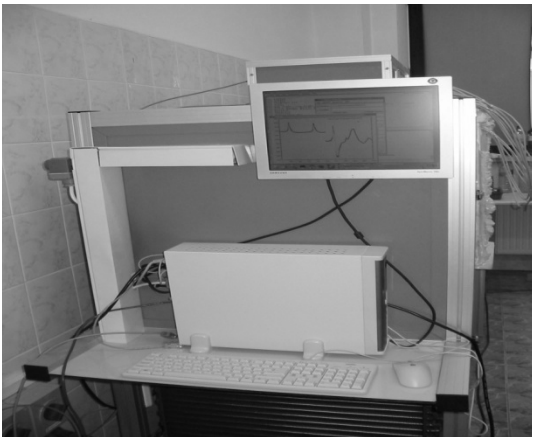


Fig. 7. Registering positions laboratory [source: own study]

Correlations among obtained values of coefficient of heat conduction permit on determination of characterizations of graphic coefficient for chance dry and wet bricks.

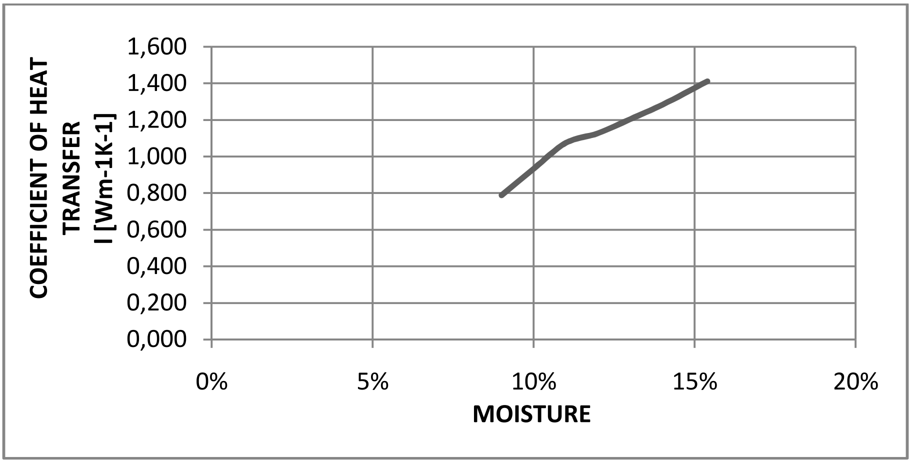


Fig. 8. Characterizations of changes of coefficient of heat transfer in wet full brick [source: own study]

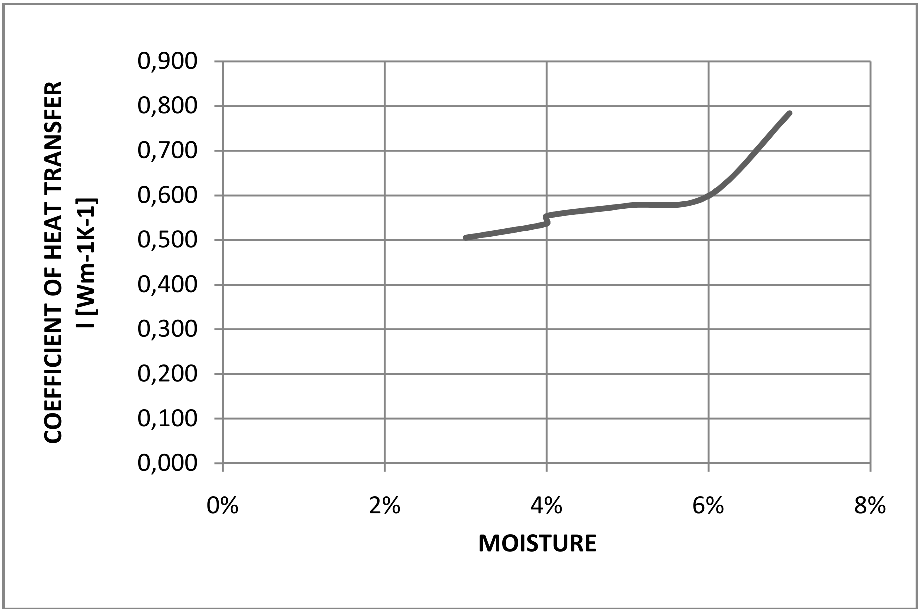


Fig. 9. Characterizations of changes of coefficient of heat transfer in dry full brick [source: own study]

Obtained results of measurements permitted on qualification of dependence of coefficient of heat transfer from internal temperatures in full red brick wet and dry.

Example – course of changes of value of coefficient of heat transfer. Simultaneously obtained results of value of coefficient of heat transfer permitted on determination of coefficient lambda. From represented below graphs results difference among courses for wet and dry bricks.

5. CONCLUSIONS

By the suitable construction of the enclosure walls composed of several slabs of different thicknesses and conductivities, we can obtain phase shift (when the time lag attains twelve hours it is the best situation), which reduce the amplitude of internal temperature inside technical chamber and, in consequence, give equivalent of using energy. The influence of this periodically changing weather temperature upon the inside storages climate is depending on the material of walls and inertial property of thermal technical spaces, it means a fruit storage.

This analysis shows the periodic variability of outside temperature, changing in periods of each day and also in the year with maximum value in the afternoon or in summer and minimum value in the night or winter time. The influence of this periodically changing temperature on the inside storages climate is depending on thermal inertia of technical spaces. The proper construction of an object with prescribed thermo-stability characteristic can use the phase difference between internal and external temperature and allow to lower costs of energy, necessary for cooling or heating the technical spaces.

REFERENCES

[1] CARLSLAW H., JAEGER,J.: *Conduction Of Heat In Solids*. Oxford University, 1959.

[2] TAKAHASHI Y., RABINS M., AUSLANDER D.: *Sterowanie i Systemy Dynamiczne*. WNT, Warszawa, 1976.

[3] JANCZAREK M. M.: *Methods Concerning Conductive Heat Transfers Through Walls Of Thermal Technical Spaces*. Matar'92, Prague, 1992, p. 166–170.

[4] BULYANDRA O. F., YANCHAREK M. M.: *Analiz Peredachi Teploti Kriz Zownischniu Stinku Skladskowo Primischenia Z Urahowaniam Dinamiki Zmin Atmosfernoi Temperature*. Harchowa Promislowist, No. 4, Kyiv, 2005.

[5] JANCZAREK M., SKALSKI P., BULYANDRA A., SOBCZUK H.: *Przewodność Cieplna Zewnętrznych Ścian Budynków W Aspekcie Wilgotności I Oszczędności Energii.* Rynek Energii, No. 4(65), Lublin, 2006.

[6] WIDOMSKI M., SOBCZUK H.: *Retentional Abilities Of Soils In Eroded Environment*, pp. 459-464, In Pawłowski L., Dudzińska M. & Pawłowski A., /Environmental Engineering/,Taylor & Francis, New York – Singapore, 2007.

[7] JANCZAREK M. M.: *Energooszczędność Eksploatacji Obiektów Budowlanych W Aspekcie Zmiennej Temperatury Atmosferycznej.* Rynek Energii, No. 1(68), Lublin, 2007.

[8] PAVLÍK Z. et al.: *Application Of Time-Domain Reflectometry Method For Measuring Moisture Content In Porous Building Materials*. Trends In Applied Sciences Research, 2007, vol. 2, no. 3, p.188–200.
[9] JANCZAREK M. M., BULYANDRA O. F.: *Charakterystyki Dynamiczne Wpływu Atmosferycznych Zmian Strumieni Cieplnych Na Powierzchnie Przegród Komór Obiektów Technicznych*. Informatyka W Technice, Lubelskie Towarzystwo Naukowe, Lublin, 2008, p. 124–128.
[10] ВИНОГРАДОВ-САЛТЫКОВ В. А., ЯНЧАРЕК М., ФЕДОРОВ В. Г., КЕПКО О. И.: *Теплометрическое Исследование Теплозащитных Своистb Ограждений*. Industrial Heat Enginneering – International Scientific And Applied Journal, vol. 31, no. 4, 2009.
[11] SUCHORAB Z., SOBCZUK H., ROŻEJ A., ŁAGÓD G.: *Comparison Of Reflectometric And Gravimetric Methods For Examination Of Sewage Sludge Additions Influence On Water Properties Of Reclamated Soils*. Ecological Chemistry And Engineering, vol. 16, no. 4, 2009, p. 257–264.
[12] STĘPNIEWSKI W., SOBCZUK H., WIDOMSKI M.: *Diffusion In Soils.* Encyclopedia Of Agrophysics, Encyclopedia Of Earth Series, Springer 2011, p. 214–220.
[13] JANCZAREK M. M., ŚWIĆ A.: *Scientific And Technological Description Of Heat And Mass Transfer Processes In Chambers*. Acta Technical Convinieties – Bulletin Of Engineering, vol. 10, 2012.
[14] JANCZAREK M. M.: *Analiza Matematyczno-Fizyczna Cieplnych Komór Technicznych*. Technologie Informacyjne W Technice I Kształceniu, Politechnika Lubelska, Lublin, 2013, p. 127–137.
[15] SUCHORAB Z.: *Noninvasive Moisture Measurement In Building Materials*, Environmental Engineering IV – Pawłowski, Dudzińska & Pawłowski (Eds) © 2013 Taylor & Francis Group, London, p. 433–439.

Mieczysław Dziubiński[1], Mieczysław Plich[2], Ewa Siemionek[3]

INVESTIGATIONS OF ALTERNATORS, STARTERS AND IGNITION SYSTEMS RELIABILITY

1. INTRODUCTION

In order to supply the power required for the starter, for ignition and fuel-injection systems, for the ECU'S to control the electronic equipment, for lighting, and for safety and convenience electronics, motor vehicles need their own efficient and highly reliable source of energy which must always be available at any time of day or night. Whereas, with the engine stopped, the battery is the vehicle's energy store, the alternator becomes the on-board "electricity generating plant" when the engine is running [5].

In order that the entire system is reliable and trouble-free in operation, it is necessary that the alternator output, battery capacity, and starter power requirements, together with the remaining electrical loads, are matched to each other as optimally as possible. For instance, following a normal driving cycle (e.g., town driving in winter) the battery must always be sufficiently charged so that the vehicle can be started again without any trouble no matter what the temperature. And the ECU'S, sensors and actuators for the vehicle's electronic systems (e.g., for fuel management, ignition, Motronic, electronic engine-power control, antilock braking system (ABS), traction control (ASR) etc. must always be ready for operation. Apart from this, the vehicle's safety and security systems as well as its signalling systems must function immediately, the same as the lighting system at night or in fog. Furthermore, the driver-information and convenience systems must always function, and with the vehicle parked, a number of electrical loads should continue to operate for a reasonable period without discharging the battery so far that the vehicle cannot be started again.

---

[1] Lublin University of Technology, Department of Automotive Vehicles, Nadbystrzycka Str. 36, 20-618, Lublin, Poland

[2] Warsaw University of Technology, Faculty of Transport, Koszykowa Str. 75, 00-662 Warsaw, Poland.

[3] Lublin University of Technology, Department of Automotive Vehicles, Nadbystrzycka Str. 36, 20-618, Lublin, Poland.

As a matter of course, millions of motorists expect their vehicle to always be fully functional, and demand a high level of operational reliability from the electrical system.

2. STARTING SYSTEMS

Internal-combustion engines must be started by a separate system because they cannot self-start like electric motors or steam engines. In starting these engines, considerable resistance resulting from compression, piston friction and bearing friction (static friction) must be overcome. These forces depend greatly on engine type and number of cylinders, as well as on lubricant characteristics and engine temperature. Frictional resistance is highest at low temperatures. The starter must crank the engine at a specified minimum speed (starting speed) in order to generate the fuel/air mixture necessary for self-sustained operation of spark-ignition engines and the spontaneous auto-ignition temperature required by diesel engines even under adverse conditions, and must support the engine as it runs up to minimum self-sustained speed after initial ignition. Electric motors (DC, AC and 3-phase), as well as hydraulic and pneumatic motors are used as starting motors for internal-combustion engines. The DC series-wound electric motor is particularly well-suited for use as a starting motor, however, because it generates the high initial torque required to overcome cranking resistance and to accelerate the power transmission components. In the majority of cases, starting motor torque is transmitted to the engine via a starter pinion and a ring gear on the crankshaft flywheel of the engine, however V-belts, toothed belts and chains are also used, as is direct transmission to the crankshaft. As a result of the high gear ratio between the starter pinion and the ring gear on the engine flywheel, the "pinion-type starter" can be designed for low torque and high speed, thus allowing small, lightweight starters to be used [6]. An additional advantage is that the energy required to start the engine can be supplied by the same battery normally used to operate the other loads in the vehicle electrical system. For this reason, the starter cannot be viewed as an independent component, but rather must be discussed as an integral part of the electrical system Fig.1.

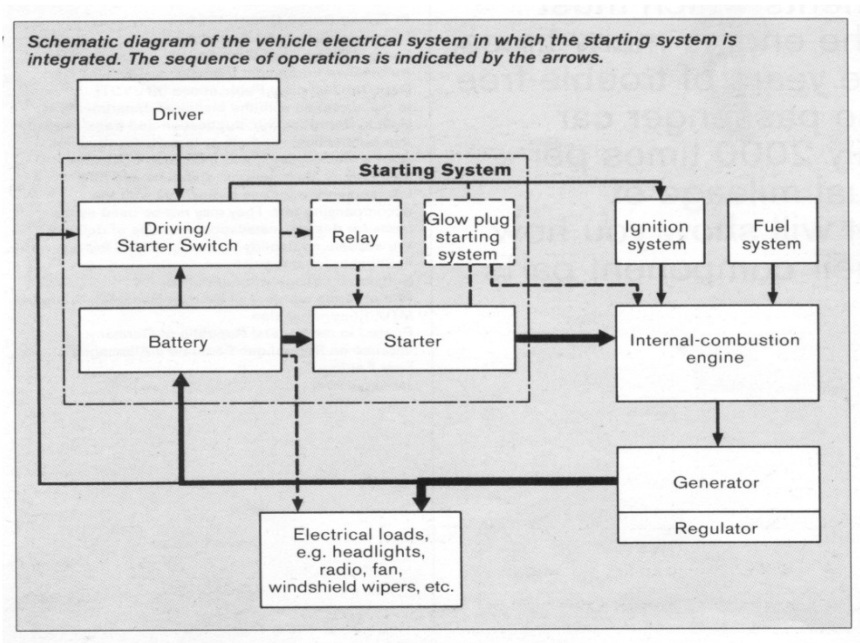


Fig.1. Schematic diagram of the vehicle electrical system in which the starting system is integrated. The sequence of operations is indicated by the arrows [5]

3. RELIABILITY AND MAINTENANCE OF STARTERS

Modern vehicles have variable purposes and operating conditions. Ensuring proper reliability of vehicles and their components in every situation is becoming necessary. Reliability tests of starters make it possible to determine their indexes. They also lead to ordering and systematizing the following problems: failure classification, determining limiting states of components wear-out or load. They identify input function factors found during operation and determine the level of their destructive effect on the starter. Information bank is significant in improving starter construction, the technology of its manufacturing as well as its maintenance manner and actual possibilities of its use. Information bank is obtained as a result of carrying out a statistical experiment. If properly worked out, it can be the basis for making proper decisions leading to ensuring the required level of reliability in vehicles under examination. The practice of applying such information proves that 3 stages can be distinguished in “the life of the starter”:

- starter construction design and designing a technological process for the starter,
- manufacturing of the starter,
- starter maintenance.

If the starter reaches such a level of reliability which is assumed for it by its construction and manufacture or not is relative to the manner of starter maintenance. It is obvious that the starter might not reach the proper level of reliability if its maintenance is not in conformity with the stated requirements.

Failures of starters in vehicles is a very important notion in the theory of reliability. Each reliability test, both reliability analysis and reliability synthesis, should have strictly defined notions of failure, conforming with the specification of the tested starter. Starter failure is a random event in witch at least one or more features of the starter, measurable or non-measurable, cease to comply with imposed requirements, i.e.

$$C_{Mi} < C_{Mi\_} \text{ or } C_{Mi} > \underline{C_{Mi}} \text{ and } C_{Nj} = 0 \tag{1}$$

for all or some indexes i=1, ..., n; j = l, ..., k.

The starter can be classified in one of the two states:
S_o – ability state, when

$$\underline{C_{Mi}} < C_{Mi} < \overline{C_{Mi}}\ , \text{ i = 1, 2, 3,...,n} \tag{2}$$

and

$$C_{Nj} = 1, \ \text{ j = 1, 2, 3,..., k} \tag{3}$$

S_1 – disability state, when

$$C_{Mi} < \underline{C_{Mi}} \qquad C_{Mi} > \overline{C_{Mi}} \quad \text{i } C_{Nj} = 0 \tag{4}$$

A transition from ability state to disability state $S_o \rightarrow S_1$ is referred to as failure of an item. The starter can get damaged as a result of constant slow irreversible wear-out and ageing processes proceeding in its components. Failures can be divided into so called natural failures and so called random failures occurring as a result of sudden rapid changes in starter features.

In the starter, failure of one component is followed by failures of other components.

Starter reliability is the probability of its correct operation in determined maintenance conditions in required time period and can be written down as the probability of an event:

$$R(t) = P\{\tau \geq t\}, \tag{5}$$

where: R(t) – reliability,
τ – operating time up to the failure,
t – required operating time.

Determining starter reliability function R(t) by means of an experiment consists in testing N identical starters in time t and in stating the number of damaged starters n. Reliability R(t) can be determined as n/N ratio for high values of N. $\frac{n}{N} \to R$ high N $(N \to \infty$ with probability close to 1)

$$R_N(t) = \frac{n(t)}{N}; \tag{6}$$

$$R_N(t) = R(t) \tag{7}$$

$R_N(t)$ – empirical reliability function.

Failure rate [$\lambda(t)$] – is a probability of conditional failure occurrence in the moment t on condition that the starter operated properly up to that moment.

$$\lambda(t) = -\frac{R'(t)}{R(t)} \tag{8}$$

Statistically estimated failure rate of starters is equal to the number of failures which occurred in time unit against the number of starters with no failures. Empirical failure rate has the shape of a step curve, approximated to a full line, which is divided into three intervals:

a) the first interval, where starter failure rate is a decreasing function, is the initial period of maintenance in which elements of lower reliability are eliminated,
b) the second interval, in which $\lambda_N(t)$=const, so called period of normal maintenance,
c) the third interval, where failure rate is an increasing function, in which wear-out and ageing failures begin to dominate.

The aim of studies was to gather data about the reliability of starters. Tests were carried out at Bendiks and Auto-Volt Bosch Service in Lublin and Bendiks in Warsaw. In the course of research, statistical distributions of starters and statistical distributions of failures, calculated on the grounds of data results sheets from mentioned above service stations, were determined. With the aid of the computer program "Statistica" and with the use of λ-Kołmogorow test of goodness of fit, reliability models of starters were made [6,7]. Fig. 2. present empirical function and reliability model of the starter.

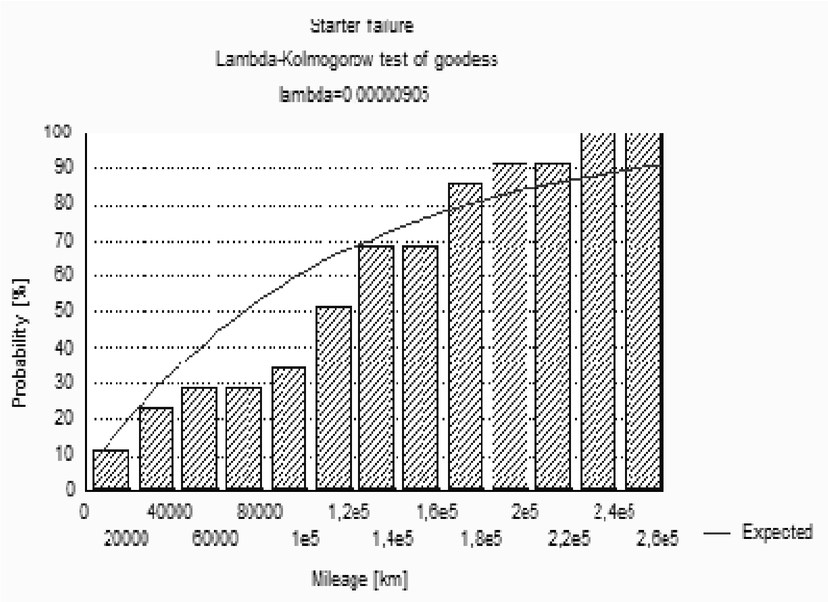


Fig. 2. Starter reliability model [5]

4. GENERATION OF ELECTRICAL POWER IN THE MOTOR VEHICLE

The electrical loads have differing duty cycles (Fig. 3). A differentiation is made between permanent loads (ignition, fuel injection etc.), long-time loads (lighting, car radio, vehicle heater etc.), and short-time loads (turn signals, stop lamps etc.). Some electrical loads are only switched on according to season (air-conditioner in summer, seat heater in winter). And the operation of electrical radiator fans depends upon temperature and driving conditions.

A computer program is used to determine the state of battery charge at the end of a typical driving cycle. Here, such influences as battery size, alternator size, and load input powers must be taken into account.

Rush-hour driving (low engine speeds) combined with winter operation (low charging-current input to the battery) is regarded as a normal passenger-car driving cycle. In the case of vehicles equipped with an air conditioner, summer operation can be even more unfavorable than winter.

The nature of the wiring between alternator, battery, and electrical equipment also influences the voltage level and, as a result, the state of battery charge. If all electrical loads are connected at the battery, the total current (sum of battery charging current and load current) flows through the charging line, and the resulting high voltage drop causes a reduction in the charging voltage [3, 4, 6].

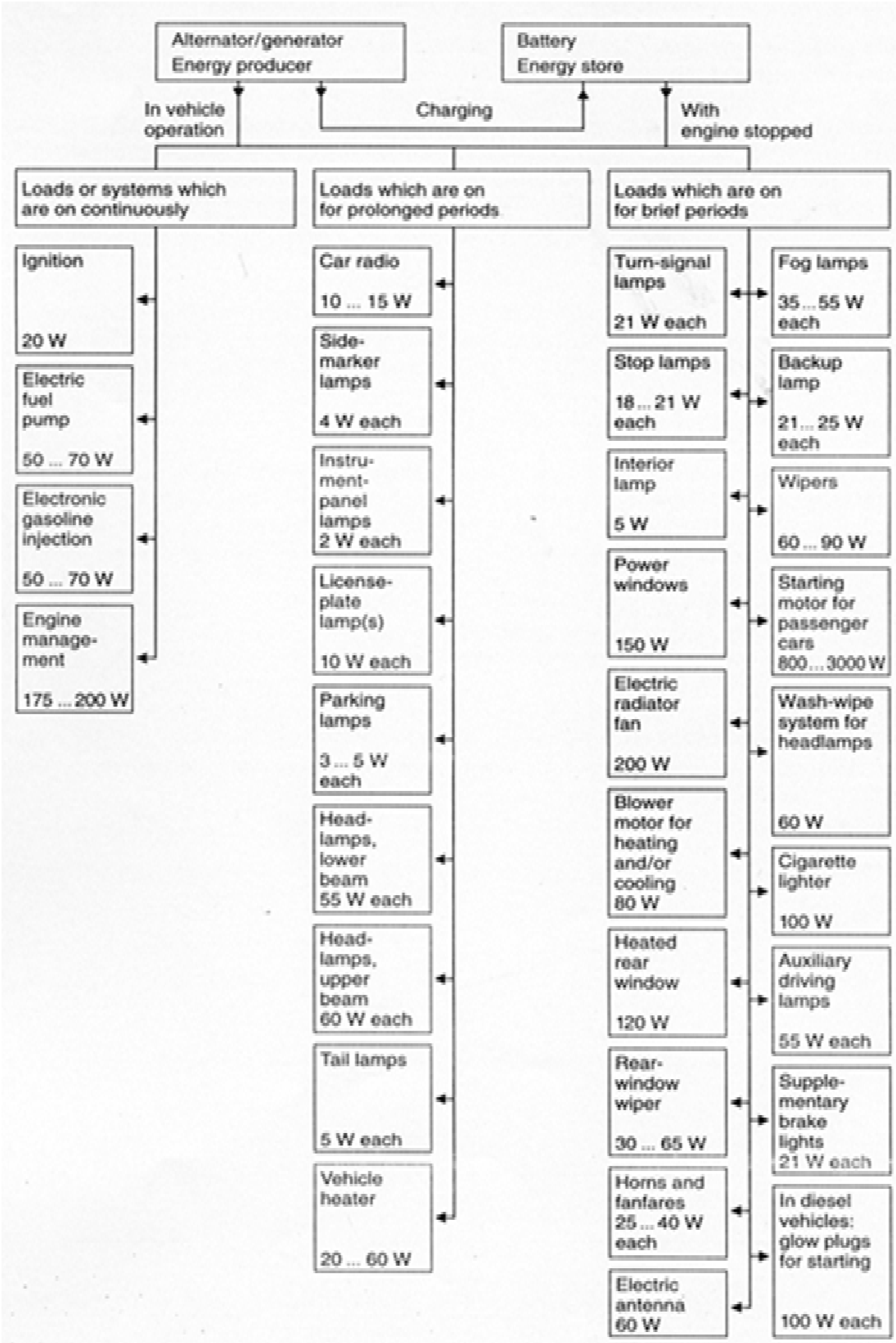


Fig. 3. Power requirements of the loads in the vehicle (average values) [5]

Conversely, if all electrical devices are connected at the alternator side, the voltage drop is less and the charging voltage is higher. This may have a negative effect upon devices which are sensitive to voltage peaks or high voltage ripple (electronic circuitry). For this reason, it is advisable to connect voltage-insensitive equipment with low power inputs to the battery. Appropriate line cross-sections, and good connections whose contact resistances do not increase even after long periods of operation, contribute to keeping the voltage drop to a minimum.

The alternator's most important characteristics are:

- It generates power even at engine idle.
- Rectification of the AC uses power diodes in a three-phase bridge circuit.
- The diodes separate alternator and battery from the vehicle electrical system when the alternator voltage drops below the battery voltage.
- The alternator's far higher level of mechanical efficiency means that they are designed to be far lighter than DC generators.
- Alternators feature a long service life. The passenger-car alternator's service life corresponds roughly to that of the engine (up to 150,000 km), which means that no servicing is necessary during this period.

5. COMPUTER TESTS OF ALTERNATOR RELIABILITY

The dynamic development of electronics contributed to the increase in the number of car elements and circuits which are powered by the alternator.

For that purpose, alternator power is being increased and new constructional solutions are being introduced. Thus a need for constant reliability test arises. Alternator tests make it possible to determine reliability, which is necessary as a comparative criterion against new constructional solutions. The tests lead to organizing the following problems: failure classification, determining wear-out limiting states during maintenance and actual possibilities of making use of reliability analysis. On the grounds of carried out failure simulation in the phase of production processing and carried out statistical experiment, information bank which is properly worked out, can be the basis for making decisions leading to ensuring the required alternator reliability level. Making use of the obtained information proves that 3 stages can be distinguished in the "life" of the alternator. Making use of reliability tests results is significant in all the phases, particularly while:

- designing alternator construction and designing manufacturing process,
- manufacturing the alternator,
- maintaining alternators.

In the phase of designing the construction and technological process of the alternator, some initial assumptions arise. They determine its purpose, construction details and operational use. Designing both the construction and technological process are the most significant stages, strongly influencing reliability and ensuring alternator proper level. That stage can be properly carried out if the condition of constructor-production engineer strict co-operation and of constructor's thorough knowledge about production plant technological potential is full-filled. Apart from constructor – production engineer co-operation, there are some basic requirements concerning proper organization of constructional and technological departments, proper technological equipment in those departments, suitably qualified staff etc. In the field of alternator construction the following methods of increasing reliability are the most crucial:

- increasing reliability and life of its constituent parts,
- choosing a proper reliability block diagram,
- adding to the alternator elements or units duplicating work (so called redundancy).

In the case of modern alternators, each element usually contributes to their reliability. Alternator reliability equals to the product of its constituent elements reliabilities. Such a dependence makes the use of highly reliable constituent elements necessary and limits the increase in the whole alternator reliability as further increase in its constituents elements reliabilities is e.g. technologically impossible and causes the increase in manufacturing costs.

Some possibilities of increasing alternator reliability can be obtained through preserving its proper reliability block diagrams. Using various reliability block diagrams theoretically leaves a lot of freedom in increasing reliability. However in practice, using those block diagrams or their combinations is restricted by constructional, technological and economic factors. The application of that method is always connected with a serious complication in the construction and is hardly ever economically justified. The solution to the problem connected with ensuring the required reliability level in the phase of alternator manufacturing is the following: "Ensure such production conditions that all constructional and technological requirements and conditions assumed in the design phase can be full-filled". The quality control system used nowadays contributes to the fact that designing technological process, so called by-pass process, and substitute materials many times does not show the decrease in quality. As a rule, alternator reliability in the maintenance process is decreased. As reliability is a time-dependent characteristic, all defects and troubles of alternators begin during their maintenance and consist in reliability level decrease and usually life shortening. Another significant problem is the fact that plants do not adhere to shop discipline in spite of their technological potential.

Then the following troubles occur:

- disregard for proper technological parameters,
- disregard for the proper order of technological operations,
- using imprecise control apparatus,
- improper assembly etc.

The proper assessment of a technological process can be obtained only through carrying out maintenance reliability tests. In that way its influence on alternator quality and parameters can be judged. The way the alternator is used decides if it reaches such a level of reliability which has been assumed in its construction and manufacture. It is obvious that alternators might not gain such a level of reliability if they are used with no regard for previously stated requirements. Alternator reliability level is determined as a result of failures occurring during its operation. The following occurrences influence the level of reliability:

1. Failures being the result of errors in the process of construction design and technology design and in the phase of alternator manufacturing.
2. Failures being the result of disregarding technical specifications assumed for the alternator in the process of its maintenance.
3. Preventive activities in the process of maintenance.

In the process of maintenance, alternator reliability can be influenced by complying with technical specifications and rising the level of maintenance process organization.

Data for the reliability model determine car mileage up to the moment of failure occurrence. With the aid of the computer program. "Statistica" and with the use of λ-Kołmogorow test of goodness of fit, alternator reliability models have been worked out, Fig.4.

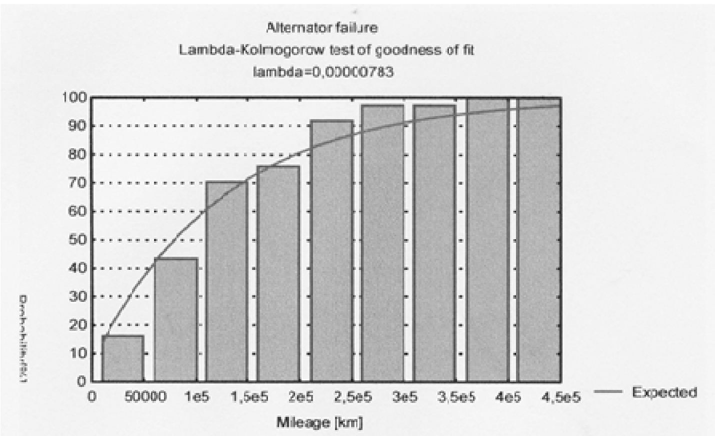


Fig. 4. Alternator reliability model [5]

6. INVESTIGATIONS OF IGNITION SYSTEMS RELIABILITY

The ignition system must function perfectly for the engine to function correctly.

Verifiable ignition timing allows the ignition to respond to variations in engine speed and load factor. On simple systems, timing is adjusted by a centrifugal advance mechanism and a vacuum control unit. Manifold vacuum provides a reasonably accurate index of engine load.

Semiconductor ignition systems also allow for other influences of the engine e.g., temperature or changes in the mixture composition. The values of all ignition timing functions are linked either mechanically or electronically in order to determine the ignition point.

The energy storage device must be fully charged before the actual ignition point.

This requires the formation of a dwell period or dwell angle in the ignition system. The energy is generally stored in an inductive storage device, and, in rare cases, in a capacitive storage device. High voltage is generated by disconnecting the primary inductor from the power supply followed by transformation. The high voltage is applied to the cylinder currently performing the working stroke. When an ignition distributor is used, the crankshaft position information required for this is provided by an appropriate mechanism via the ignition distributor drive. In the case of stationary voltage distribution, an electrical signal from the crankshaft or the camshaft provides the position signal. The connecting elements (plugs and high-tension cable) convey the high voltage to the spark plug. The spark plug must function reliably in all engine operating ranges in order to ensure consistent ignition of the mixture. The excess-air factor λ and the cylinder pressure which is determined by charge and compression have, together with the spark-plug electrode gap, a crucial influence upon the required ignition voltage and , thus, upon the required secondary available voltage of the ignition system. Approximately 0.2 mJ of energy is required per individual ignition for igniting an air-fuel mixture by electric spark, providing the mixture has a stochiometric composition. Rich and lean mixtures require over 3 mJ. This amount of energy is but a fraction of the total energy contained in the ignition spark, the ignition energy. Is insufficient ignition energy is available, ignition does not occur; the mixture cannot ignite and there are combustion misses. This is way adequate ignition energy must be provided to ensure that, even under worst-case external conditions, the air-fuel mixture always ignites. It may suffice for a small cloud of explosive mixture to move past the spark. The cloud of mixture ignites and, in turn, ignites the rest of the mixture in the cylinder, thus initiating fuel combustion. Good induction and easy access of the mixture to the ignition spark improve the ignition character-ristics as do long spark duration and a long spark or large electrode gap. Intense turbulence of the mixture also has a similarly favourable effect providing that adequate ignition energy is available. The spark position and spark length are determined by the dimensions of the spark plug. The spark duration is determi-ned by the type and design of ignition system and the instantaneous ignition conditions. The spark position and accessibility of the mixture to the spark plug influence the exhaust gas, especially in the idle range. Particularly high ignition energy and a long spark duration are favourable in the case of lean mixtures. This can be demonstrated using an engine at idle.

Fouling of the spark plug is also an important factor. If spark plugs are badly fouled, energy is discharged from the ignition coil via the spark-plug shunt path during the period in which the high voltage is being built up. This shortens the spark duration, thus affecting the exhaust gas and, in critical cases (if the spark plugs are badly fouled or wet)may result in complete misfiring. A certain amo-unt of misfiring is normally not noticed by the driver but does result in higher fuel consumption and may damage the catalytic converter.

The ignition angle αz or the ignition point has an important influence on the exhaust-gas values, the torque, the fuel consumption and the driveability of the spark-ignition engine. Failures of ignition systems in vehicles is a very important notion in the theory of reliability. Each reliability test, both reliability analysis and reliability synthesis, should have strictly defined notions of failure, conforming with the specification of the tested ignition system.

Statistically estimated failure rate of ignition system is equal to the number of failures which occurred in time unit against the number of ignition system with no failures.

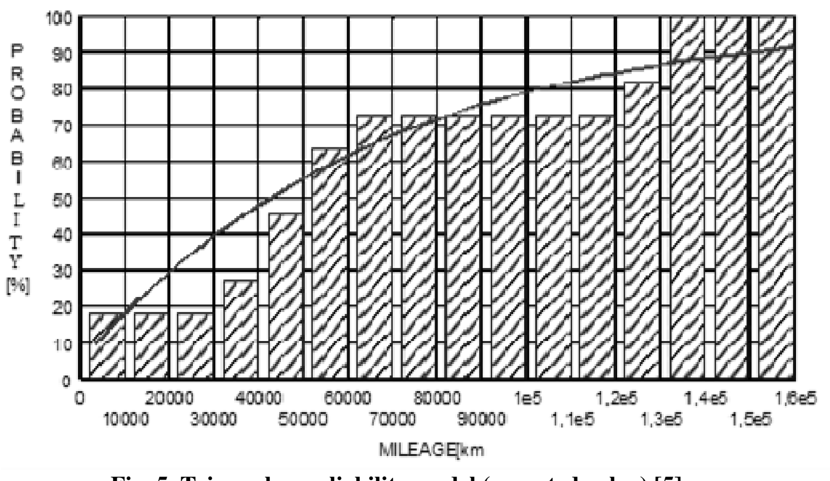


Fig. 5. Trigger box reliability model (expected value) [5]

The aim of studies was to gather data about the reliability of ignition system. Tests were carried out at Auto-Volt, Bosch Service in Lublin. With the aid of the computer program “Statistica” and with the use of λ-Kołmogorow test of goodness of fit, reliability models of ignition system were made (Fig. 5.)

7. CONCLUSIONS

Gathered information about reliability, parameters and failures of starter particular components makes it possible to state requirements for construction and changes of functional and diagnostic parameters of a given starter type.

The analysis of time up to the failure occurrence (or the number of covered kilometers together with test conditions) makes it possible to establish and identify failure causes and to assess the possibility of selecting and improving starter particular components.The analysis of starters reliability provides a wide range of development possibilities in computer modelling of recovery processes and reliability diagnostics.

Gathered information about alternator reliability, its parameters and the use of proper materials make it possible to formulate requirements concerning the construction and assembly technological process. Recognizing and identifying the causes of alternator elements failures makes it possible to replace it with another one, and also to state new operating conditions. Effective impact on reliability can be realized on the grounds of detailed analysis and synthesis of alternator design, manufacture and maintenance.

Gathered information about reliability, parameters and failures of ignition system particular components makes it possible to state requirements for construction and changes of functional and diagnostic parameters of a given ignition system type. The analysis of time up to the failure occurrence (or the number of covered kilometers together with test conditions) makes it possible to establish and identify failure causes and to assess the possibility of selecting and improving ignition system particular components.

The analysis of ignition system reliability provides a wide range of development possibilities in computer modelling of recovery processes and reliability diagnostics. Stating that ignition system technical state is dependent upon structure parameters values and is determined by them is crucial for explaining the essence of diagnostics. However, it is not sufficient in practice because generally it is impossible to measure object structure parameters without its disassembly. It must be added that output parameters course is dependent upon ignition system technical state.

A model of reliability can be created for ignition system being characterised by optional structure. This method basing upon analysis of effect of failure (failure of operating) of a subsystem select determines the consequences of such failures for operation of whole system and determines conditions resulting in each type of failures.

REFERENCES

[1] DUDA J.: *Zintegrowany rozwój wyrobu – strategia PLM*. CA Systems and Technologies, Żilina, 2003, p. 20–27.

[2] DUDA J., SAMEK A.: *Structural analysis of the conventional and concurrent engineering*. Proceeding of the Eight International FAIM Conference Flexible Automation and Intelligent Manufacturing, 1-3 July 1998, Poland, USA.

[3] DZIUBIŃSKI M.: *Computer control of alternator manufacture*. Manufacturing Engineering, Presov, 2003, p. 57–61.

[4] DZIUBIŃSKI M.: *Computer tests of alternator reliability*. CA System and Technologies, Integration and Intelligence of CA System, Żylina,2003, p. 145–152.

[5] DZIUBIŃSKI M.: *Maintenance and Reliability Electrical Equipment of Engine*. Copenhagen 2007, p. 90.

[6] DZIUBIŃSKI M.: *Reliability aspects in constructing vehicle electronic equipment*. Journal of Middle European Construction and Design of CArs , Praha, 2003, p. 44–48.

[7] DZIUBIŃSKI M.: *Reliability aspects in manufacturing of starter*. New Ways in Manufacturing Engineering, Presov, 2004, p. 385–390.

[8] DZIUBIŃSKI M., CZARNIGOWSKI J., NIEOCZYM A.: *Simulation Test of Injection System Reliability*. International Journal of Materiale&Structural Reliability, vol. 4, no. 1, Thailand, 2006.

[9] DZIUBIŃSKI M., PLICH M.: *Modelowanie i symulacja stanów niezawodności układu zasilania elektrycznego pojazdu*. XL Szkoła Niezawodności, Szczyrk, 2012.

[10] HLAVNA V.: *A cooling comustion engine in a non-conventional energetic system*. Teka Komisji Motoryzacji, Kraków, p. 101–108.

[11] LISCAK S.: *Spolahlivost v prevadzke cestnych vozidiel*. Żilinska Univerzita v Żiline, Vydavatelstvo ŻU, 2002, p. 193.

[12] MARCINCIN J. N.: *Tendencie vo vyvoji spickovych CAD/CAM/CAE systemov*. Strojarstvo, roc.3, c.11, 1999, p. 36–37.

[13] MARCINCIN J. N.: *Systemy pre spravu a riadenie informacii o vyrobkoch – PDM*. Strojarstvo, roc. 5, c. 9,2001, p. 14–15.

[14] MARCINCIN J. N., KARNIK L.: *Perspektivy rozvoja komplexnych podnikovych informacnych systemom*. Zbornik Informatika a algoritmy'99. FVT, Presov, 1999, p. 20–23.

[15] MARCINCIN, J. N., PETIK A.: *Teoreticke zaklady pocitacovej podpory vyrobneho inzinierstva*. FVT TU, Presov, 2000, p. 157.

[16] NOVAK-MARCINCIN J., HAVRILA M., BARON P.: *Application of CA Systems in Technological Disassembly Process Planning*. New Ways in Manufacturing Engineering, Presov, 2004, p. 476–479.

[17] SIEMIONEK E.: *Energy consumption in the motion of the vihicle with electric propulsion*. Teka Komisji Motoryzacji i Energetyki Rolnictwa PAN, 2011, p. 320–326.

[18] SIEMIONEK E.: *Badania eksploatacyjne pojazdu jednośladowego z napędem elektrycznym.* Selected issues from machine building and exploitation, Lublin, 2014, p. 61–75.

Marek Błaszczak[1]

THE INFLUENCE OF SYNERGISM IN THE MODELING OF PHASE TRANSITION PLOT ALGORITHMS FOR ALLOYS

1. INTRODUCTION

Modeling of processes occurring during heat treatment of alloys is a quite complex a question, due to the large number of factors influencing the end effect of the conducted process. Temperature is of basic importance, as well as other environmental factors, that influence each other to a larger o lesser degree. The element that has a major influence is the chemical composition of alloy, particularly important in case of-multi element alloys. The components of the alloy of given properties that bond together in some circumstances have an effect on other components. This effect can take the form of additive synergism, where the achieved effect is the sum or even the exponentiation of the elements introduced jointly. The available literature shows this aspect in quite a generalized way, as a system of mixtures that only influences the set physical properties of an alloy. The example may be tungsten, which reduces grain size, improves the tempering properties, hardness and reduces wear. But in connection with other alloy additives this effect will no longer be so explicit and obvious.

Similar phenomenon that can be observed in case of alloys is the catalysis effect that should not be equated with the synergy effect. Still we can observe some analogies in taking a closer look at it. What is problematic is the acceptance of temperature in the role of a component – catalyst.

The models of thermal processing available in the literature are an example of difference between experimental and analytic data, which may be the result of the multidirectional synergism. Introduction of additional elements to the modeling process, such as the analytic equations, multi-criterion analysis, database systems, heuristic algorithms, numerical methods and neuron networks proved to have a satisfactory effect in form of hybrid solutions.

[1] Politechnika Lubelska, Wydział Mechaniczny, Instytut Technologicznych Systemów Informacyjnych, ul. Nadbystrzycka 36, 20-618 Lublin, POLAND

The article proposes assumptions that treat the alloy components as elements of a mixture of chemical elements with set physical properties, which can lead to creation of different thermodynamic systems, depending on the conditions.

2. CALCULATION OF THE TEMPERATURE FIELD

The temperature field in a metal material subjected to heat treatment has substantial importance for the prediction of the microstructure that is forming and final properties of the material subjected to that heat treatment. The heat field is described by the Furier-Kirchhoff differential equation that in a system of cylindrical coordinates adopts the following form

$$\frac{\delta T}{\delta \tau} = \frac{\lambda}{c_p \rho}\left(\frac{\delta^2 T}{\delta r^2} + \frac{1}{r}\frac{\delta T}{\delta r} + \frac{1}{r^2}\frac{\delta^2 T}{\delta \varphi^2} + \frac{\delta^2 T}{\delta z^2}\right) + \frac{q_v}{c_p q}$$

where: T – Temperature,
τ – time,
λ – heat conductivity,
c_p – specific heat capacity in conditions of constant pressure,
ρ – own mass,
q_w – the volumetric efficiency of heat source,
r, φ, z – cylindrical coordinates.

The volumetric heat sources included in this mathematical model are used to take account for the heat of the phase transitions in solid state. They are described by the equation [3]:

$$Q_v = \sum_i H_i \frac{\Delta \eta_i}{\Delta t}$$

where: H – the heat of *i*-th phase transition,
$\Delta\eta_i$ – the increase of volume in the *i*-th phase.

The heats of phase transitions are defined by the components:

$H_{\gamma\to\alpha}(T_c)=0{,}00064156\cdot T_c^3 - 0{,}59347\cdot T_c^2+245{,}24\cdot T_C - 145423$
$H_{\gamma\to P}(T_c)=0{,}00093038\cdot T_c^3 - 1{,}0536\cdot T_c^2+475{,}96\cdot T_C - 212728$
$H_{\gamma\to B}(T_c)=0{,}00077541\cdot T_c^3 - 0{,}81671\cdot T_c^2+365{,}01\cdot T_C - 145423$
$H_{\gamma\to M}(T_c)=8{,}25\cdot 10^4$

where: $H_{\gamma\to\alpha}$[J/kg] is the heat of transition of austenite into, correspondingly α-ferrite, P – perlite, B – bainite, M – martensite, T_C [ºC] is the temperature.

In case of objects with complicated shapes the temperature fields can only be calculated with the use of numerical methods. One of these is the Finite difference method, FDM [3].

Analytic solutions for objects with simple, geometric shapes are presented in form of Furier series. In case of a plate the Fourier series include the trigonometry functions of cosines and sines, and in case of cylinders – Bassel function of the first kind, that is one of the specific solutions of Bassel's differential equation.

The Bassel's function of the first kind and n-rank has the form of:

$$J_n(z) = \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{z}{2}\right)^{n+2k}}{k!} (n+k)!$$

Where $|z| < \infty$

For n = 0

$$J_0(z) = 1 - \frac{\left(\frac{z}{2}\right)^2}{(1!)^2} + \frac{\left(\frac{z}{2}\right)^4}{(2!)^2} - \frac{\left(\frac{z}{2}\right)^3}{(3!)^3} + \ldots$$

The calculated values for the six zero points of the $J_0(z)$ function, used in analytic solutions for heat conductivity equation for a cylindrical set of coordinates is listed in tabel 1.

Tab.1. The value of the first zero points of the Bessel's $J_0(z)$ function[3] [source: own study]

Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
2,4048	**5,5201**	**8,6537**	**11,7915**	**14,9309**	**18,0711**

3. SOLUTION OF HEAT CONDUCTIVITY EQUATIONS WITH USE OF THE FINAL DIFFERENCE METHOD

The numerical solution of the heat field equation requires the knowledge of the T (r, φ, z, 0) initial condition and the boundary conditions appropriate for heat treatment conditions. In the practical application of heat treatment most common boundary conditions are the ones of I or III kind, described by the equation:

$$T(x, y, z, \tau)_{(x,y,z)\in A} = \phi(x, y, z)_{(x,y,z)\in A}$$

$$\frac{\delta T}{\delta n}_{(x,y,z)\in A} = \pm\frac{\alpha}{\lambda}\left[T(x,y,z,\tau)_{(x,y,z)\in A} - T_{sr}\right]$$

where: A – boundary surface,
T_{sr} – medium temperature,
α – heat absorption coefficient.

The FDM replaces the temperature T derivatives with appropriate differential quotients. In case of a three-dimensional area with rectangular system of coordinates, the analyzed area is divided with a rectangular mesh, with openings corresponding to the steps Δx, Δy, and Δz; the choice of steps depends on the size of analyzed object and the predicted trajectory of isotherms.

4. RECTANGULAR SYSTEM OF COORDINATES

In the Explicit FDM replaces the differential quotients as approximate of the first derivate of temperature in time and the differential quotient of the symmetrical of the second rank in place of two temperature derivatives in spatial coordinates results with the following equation [3,4]:

$$T_{i,j,l}^{k+1} = v(T_{i+1,j,l}^{k} + T_{i-1,j,l}^{k})\Delta_1 + \upsilon\left[(T_{i,j+1,l}^{k} + T_{i,j-1,l}^{k})\Delta_2 + (T_{i,j,l+1}^{k} + T_{i,j,l-1}^{k})\Delta_3\right] +$$
$$+\left[1 - 2\upsilon(\Delta_1 + \Delta_2 + \Delta_3)\right]\cdot T_{i,j,l}^{k}$$

where:

$$\upsilon = \frac{\lambda\cdot\Delta\tau}{c_p\cdot\rho\left[(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2\right]}$$

The *i, j, l* indexes mark the *x, y, z* directions, appropriately.

As the equations show, the temperature in the node (I,j,and l) in the k+1 time interval is calculated on the basis of knowledge of the temperature of a given node and its vicinity in the previous k time step.

In order to secure the stability of the numerical solutions the υ parameter has to be carefully chosen. The value of this parameter can't exceed 0.5 in case of calculation in single dimension system, 1D.

Using the III kind of the border condition the temperature in the nodes located on the borders of the analyzed area in the system of rectangular coordinates is calculate by the introduction of the fictional temperature a spatial step away from the border of the area.

5. CTP BALANCED GRAPH METHOD, BASED UPON THE MAYNIER MODEL

On the basis of information on temperature field T(x,y,z,τ) the pace of cooling in every point of the object subjected to heat treatment is known, thus allowing foreseeing the changes in microstructure from the cooled austenite, based upon the known characteristics of kinetics of decomposition (CTP_i – isothermal graph and the CTP_c – constant cooling graph.) It is based on calculation, on the basis of the chemical composition of steel and the conditions of austenite forming, of the ten characteristic values of cooling pace for the temperature of 700 ºC, υ_{700}, that secures the set structural composition of steel. The works of Maynier give us the dependencies between the υ_{700} paces and the chemical composition and austenite forming parameters, and the equations describing the hardness of the structural components that are formed in decomposition of austenite in the function of chemical composition and cooling pace.

The examples of applications using the Maynier's model are given in many works, but it should be stated, that the equations calculated on the basis of the empirical CTP_c graphs allow us to predict the composition of the microstructure only with a limited precision, especially since the authors give only 8 characteristic pace equations out of 10 developed. A more precise result of the hardness calculation in a point with known cooling pace can be achieved by using the empirical tempering curve for calculations. The empirical dependency $v_{700} = f(l)$ is given for some standards for tempering tests. It should be taken into account that such a characteristic is an average value for construction steels as the pace of cooling, apart from the external conditions such as the parameters of cooling medium, is also influenced by the thermo-physical properties of steel, which in turn depend on its chemical composition.

6. PHASE TRANSITIONS

In order to determine the kinetics of phase transitions of solid state the macroscopic model of changes was utilized, constructed on the basis of analysis of CTP_c or CTP_i graphs. In this model the determination of the increase of the austenite phase is based upon Avrami's empirical equation [2]

$$\tilde{\eta}_\gamma(T,t) = 1 - \exp(-b(T)t^{n(T)})$$

where: the n(T) and b(T) functions define the dependencies,

$$n(T) = 6{,}12733 / \ln\left(\frac{t_f(T)}{t_s(T)}\right),\ b(T) = \frac{0{,}01005}{t_s^{\,n(T)}}$$

this equation is only used to determine the kinetics of transition in cases of heating slower, than 100K/s. Heat treatment procedures with use of faster heating requires a modification and the use of a modified Koistinen – Marburger equation [2,3]

$$\eta_{(i)}(T,t) = 1 - \exp\left(-k_\gamma(T_{s\gamma} - T)\right),\ k_\lambda = \frac{4{,}60517}{T_{s\gamma} - T_{f\gamma}}$$

comparison of analytic calculations with experimental data is presented in Fig. 1.

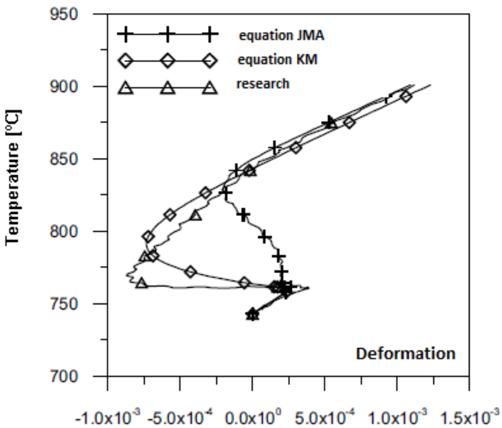


Fig. 1. Comparison of the kinetics of formation of austenite with numerical models and experiment [3]

Not just the speed of heating and cooling have the decisive influence on the kinetics of transition, but also the markedly present in case of martensite transition – state of tension. It is thus required to modify the equations describing the kinetics of phase transition, in order for the model to include the influence of mechanical phenomena on the changes in material structure.

During phase transitions visible changes in volume of the material processed with heat occur. This phenomena is the consequence of thermal and structural deformations. It is determined with use of the following formulas:

$$d_\varepsilon^{\,T} = \sum_i \alpha_i(T)\eta_i dT,\ d\varepsilon^{ph} = \sum_i \varepsilon_i^{\,ph}(T)d\eta_i$$

where: α_i (T) are the thermal expansion coefficients for austenite, bainite, ferrite, martensite and pearlite.

7. CONCEPTS FOR MODELING HEAT PROCESSING

Use of numerical methods for modeling of heat processing processes would allow the limitation of time necessary for choice of material for preexisting materials and the design time of new alloys. The first set of tools are software applications and the analytic tools using the databases based upon the standards, that interpret and broaden the already preexisting nomograms of the relations of the treatment parameters with the characteristic features of the processed object [2].

In analyzing the graphs for phase transitions in literature [2,4] we can accept, that the lines dividing each of the phases designate both the beginning and the end of transition. But we must also concentrate on the fact, that these points can also designate the places in which the kinetics of the whole transition is changed. One of the approaches, resulting from the analysis of the graph, is the adoption of the assumption that every phase transition occurs thanks to a global kinetic (S1 model). The other method is to delimit all the transitions as not interconnected and to ascertain the starting and finishing times of the transitions individually (the S2 model) [4].

The model of global kinetics requires adopting some assumptions. If a phase transition during cooling is the first one, based upon the time the CTP_c graph crosses the temperature curve, the time of start of the transition is ascertained and, next – the time of finishing of the transition and the maximum percentage of the transition. Based upon that data the time for end of all transitions can be determined [2].

The CTP_i graphs are usually used for analysis of phase transitions for isothermal cooling, and this is also what they were created for. But there is still the possibility to use the CTP_i graph for the analysis of phase transitions in case of constant cooling.

8. NUMERICAL MODELS OF PHASE TRANSITIONS

The work on modeling heat treatment uses a number of solutions that have common features. As entry parameters the data based on datasheets for selected construction steels or alloy steels thermo-physical properties were adopted, the α heat absorption rates for different cooling media (air, oil, water). The description of it is most commonly presented as a polynominality of a given parameter in temperature, or in table format. Based upon the information on the shape and dimensions of the object the mesh of nodes is generated, for which the temperature will be calculated. Further input data are the temperature for austenite forming, and the field of temperature calculated with a computer program with use of FDM method and the nodes of a chosen cross-section for the value of the v_{700}, as the average cooling speeds in temperature ranges of 500–800ºC, further registering the changes of temperature with time in selected points of the volume and the distribution of temperatures in selected cross-sections in a given time.

The v_{700} dependencies generated based upon calculations and the standards for tempering tests are presented in Fig. 2.

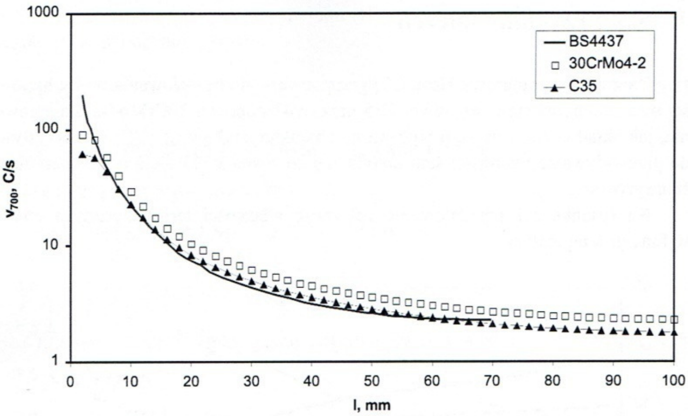


Fig. 2. Comparison of the dependency of the v_{700} speed from the temperature in the function of distance from the front of Jominy's sample for steels C30 and 30CrMo-4-2 and the BS4437 standard [2]

The tempering curve also show some differences between the calculated and experimental values. For distances in excess of 30mm of the front of the sample the experimental values are approximately 30HV higher than those which were calculated Fig. 2 [2].

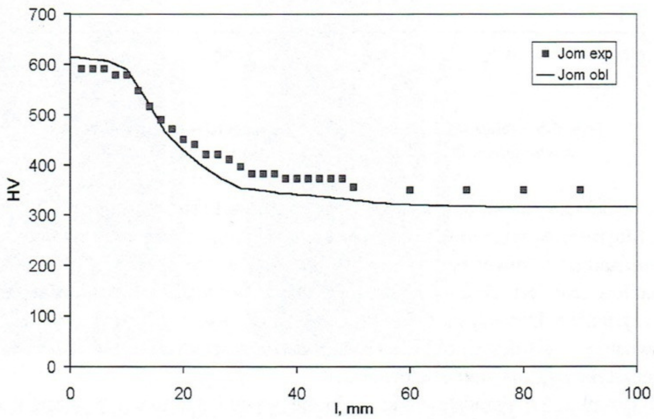


Fig. 3. Comparison of experimental and calculated steel tempering curve for the 30CrMo4-2 steel [2, 5]

9. CONCLUSIONS

Original software programs developed in the literature [4] show the complexity of the problem. The process simulation models contain only a quite limited scope of materials, which confirms there is still need to include the additional individual physiochemical properties characteristic for a given system. Corrective elements are introduced in form of parameters or coefficients, that to a lesser or larger extent depend on the specific and characteristic features of the material and the environment for thermal processing in general. Large number of works also adopts presumptions that aim at making the transition characteristics more real. The presented characteristics of phase transitions after heat treatment are based on mathematical models (the FDM method) and do not trace fully the experimental results, because apart from the already known mechanisms for structural transition, there are most probably additional processes, including the chemical reactions, of mutual influencing of the basic alloy components, as well as the additives and inclusions. This question is a very developed, and multi-thread one, but the first results of the analyses confirm such a regularity in case of the alloys with participation of the fourth period elements, based on transitional metals. Also the elements such as manganese in form of SMn but also phosphorus that directly influences the increase in steel friability. Tungsten may be another example, resulting in small grains, increase in tempering possibility, hardness and reduces wear.
Another phenomena observed is the catalysis, but its mechanism Romains unknown, pending further analysis.

The dependencies due to the complexity have to be verified with use of multidimensional analysis with use of neuron recurrence networks and self-organizing mapping. Initial analyses gave satisfactory results in form of hybrid solutions confirm the presence of synergy, but its exact mechanism is pending results of further analysis.

REFERENCES

[1] LEE K.: *Characteristics of heat generation during transition in carbon steel*. Scripta Materialia. No. 40/1990.

[2] ADRIAN H.: *Numeryczne modelowanie procesów obróbki cieplnej*. Wyd. AGH. Kraków 2011.

[3] BABEŁ J., KULAWIAK A.: *Modelowanie odkształceń strukturalnych procesu obróbki cieplnej*. Modelowanie Inżynierskie. Wyd. Politechniki Śląskiej, Gliwice 2011.

[4] DEREŃ J., HABER J., PAMPUCH R.: *Chemia Ciała stałego*, PWN, Warszawa 1975.

[5] *Norma BS 4437*.