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Contents

Editorial

Dear authors, dear readers,

this issue is completed after the end of season 2021 and we have collected five papers containing various topics in information technology and theory. The epidemic measures are over and we are going to run our normal activity and take part in various scientific events - we hope that the contents of next journal volume will grow to more extent. In our area, an interesting special event is planned in September 2022 - an International Conference *Cybernetics & Informatics 2022*, organised by our Slovak Society of Cybernetics and Informatics, in Visegrád, Hungary, under the auspices of Faculty of Electrical Engineering and Information Technology at Slovak University of Technology in Bratislava. Contributions are welcome, full details at webpage http://ki2022.sski.sk/

Despite of complicated period 2020 - 2021, our Faculty of informatics received a constant interest from young graduated as well as older employed people to enter our study program. Besides of two promised issues of journal a year, we would like to produce in the future some additional issues covering selected professional events and student projects. Another special attempt is to produce monotematic editions of journal, after the negotiation with joined communities of experts. Your forthcoming papers and contributions are welcomed around the year.

Juraj Štefanovič
ITA Executive Editor

CONTRIBUTION TO MODELING OF HYDROGEN PEM FUEL CELLS THERMAL PROCESSES

Matej Barát, Michal Stromko, Viktor Ferencey

Abstract:

This contribution deals with thermal modeling and simulations of the air-cooled PEM (Proton Exchange Membrane) fuel cell for power systems of transportation applications. PEM fuel cell is an electrochemical energy conversion device which converts chemical energy of hydrogen and oxygen directly and efficiently into electrical energy with waste heat and liquid water as by-products of the reaction. There is a number of advantages to a PEM fuel cell powered electromobiles that use hydrogen such as energy efficient and environmentally benign low temperature operation, quick start-up, compatibility with renewable energy sources and ability to obtain a power density competitive with the internal combustion engine in the perspective. Thermal analysis and thermal modeling of the air-cooled fuel cells are, however, a major problems that stems from a low operating temperatures of PEM fuel cell stacks in contrast to the conventional internal combustion engines. In the present study, a numerical thermal model is presented in order to analyse the heat transfer and predict the temperature distribution in air-cooled PEM fuel cells. In order to validate the performance of the created analytical simulation model, comparisons of the data obtained through experimental measurements in the Fuel Cells laboratory have been made.

Keywords:

PEM fuel cells, Power system, Thermal engineering, Temperature, Heat transfer, Air cooling, Hydrogen fuel, Electrochemical device, Conversion, Temperature distribution.

ACM Computing Classification System:

Hardware, Power and energy, Thermal issues, Energy generation and storage.

Introduction

The Proton Exchange Membrane Fuel Cell (PEM FC) is very flexible in terms of its power and capacity requirements, its long-life service, good ecological balance and very low self-discharges [1].

PEMFC offers high power density, quick start-up and low operating temperatures as well as rapid response to varying operational loads in many applications [2]. Currently, a PEM FC with a net power density of 1kW/L has been achieved [4].

Air-cooled proton exchange membrane fuel cells (PEM FCs), combining air cooling and oxidant supply channels, offer a significantly reduced bill of materials and system complexity compared to the conventional, water-cooled fuel cells. In air-cooled PEM FC systems, ambient air is applied freely as the cooling medium which means that the cooling environment is highly influenced by the ambient temperature. High inlet air temperature would reduce the cooling efficiency.

Air-cooled fuel cell systems combine the cooling function with the cathode flow field and reduce overall cost by eliminating a lot of auxiliary systems required for conventional fuel cell designs (water cooling loop, air compressor and humidifier) [4].

Operation of a proton exchange membrane fuel cell (PEM FC) is a complex process that includes electrochemical reactions coupled with transport of mass, momentum, energy and electricity [5].

The operating conditions for the best performance require a balance between temperature, humidity and reactant flow rates in order to avoid flooding of electrodes [6]. The sensitivity of PEM fuel cell stacks to temperature is mainly related to the required moisture levels in the membrane that is hydrated from water back-diffusion flux from the cathode to the anode. When the operating current density increases, the effects of temperature on membrane hydration decrease slightly.

However, heat is also needed for improved reaction kinetics at the catalyst layers. The effects of the heat to the operation of a fuel cell are subjective and complex. Heat is needed to improve the reaction kinetics, but too much heat would lead to an increase in energy losses [7]. Therefore, thermal management of PEM fuel cells needs to balance delicately with both requirements.

The Proton Exchange Membrane Fuel Cell (PEM FC) is very flexible in terms of power and capacity requirements, its long-life service, good ecological balance and very low self-discharges [4].

Temperature is a crucial parameter for PEM fuel cell performance which directly or indirectly affects the reaction kinetics, transport of water, humidity level, conductivity of membrane, catalyst tolerance, removal of heat or thermal stresses in the membrane etc. [4].

To conclude, the performance of the fuel cell increases as the temperature increases from room temperature to 80°C, further increase in temperature results in a current density dependent performance. The best performance was observed at around 80°C with 3 bars of absolute back pressure and 100% relative humidity.

For small size and performance of stacks (below 100W), the cooling can be achieved only with cathode air flow. A disadvantage here is that it requires relatively bigger channel size for cathode side of the stack compared with the anode side which consequently increases the volume of the stack. Stacks bigger than few hundred watts require a separate cooling channels.

1 Heat Sources in PEM FC

The electrical performance of a PEM fuel cell dictates the generated thermal energy within the stack. The theoretical power curve of a fuel cell can be obtained by establishing electrochemical models based on the Nernst equation and subsequent voltage losses within the stack. Higher voltage losses at a specified current density lead to a higher heat generation. During the operation of a PEM FC, hydrogen molecules are supplied at the anode and split into protons and electrons. The polymeric membrane conducts protons to the cathode while the electrons move from anode to cathode through an external load powered by the cell. Oxygen (from air) reacts with the protons and electrons in the cathode half-cell where water and heat are produced.

The overall reaction of a PEM fuel cell is: $\mathbf{H_2 + ½\, O_2 > H_2O}$ **+ electrical energy + heat energy**

1.1 Heat Generation

All the chemical energy that we have available in a fuel cannot be converted into useful work (electrical energy) because of the enthalpy (entropy) change during a chemical reaction. The heat generated within fuel cells is assumed to be the heat generated mainly at the electrochemical reaction sites of the cathodes. Generally, to determine the amount of heat produced by a fuel cell, an energy balance for a fuel cell stack can be provided:

$$\sum_i H_{i,in} = \sum_i H_{i,out} + P_{el} + \dot{Q}_{gen}, \tag{1}$$

or:

$$\dot{Q}_{gen} - \Delta H_i + P_{el} = 0, \tag{2}$$

where: $H_{i,in}, H_{i,out}$ are the enthalpies of reactants and products [kJ/kmol], P_{el} is the electrical power generated by the fuel cell [W], $\dot{Q}_{gen}$ is heat generated by the fuel cell, [W].

The amount of heat generated can be estimated using the simplified relations based on the energy balance of the system and depending on the state of water formed [7]:

$$\frac{I_{FC}}{nF} H_u n_{cell} = I_{FC} E_{cell} n_{cell} + \dot{Q}_{gen}, \tag{3}$$

where: H_u is low heating value of hydrogen [kJ/kg].

If the water exists as vapor at room temperature, then the E_{Nernst} voltage is 1.254 [V] and the stack thermal power P_{th} is dependent on the current produced and cell voltage [6]:

$$\dot{Q}_{gen} = P_{th} = (E_{Nernst} - E_{cell}) I_{FC} n_{cell} \tag{4}$$

A fuel cell stack may dissipate its heat energy by internal as well as external mechanisms. Internal heat removal by the cathode fluid stream is more significant than the anode fluid stream as the exothermic reactions occur at the cathode and produced water absorbs the generated heat.

A simple way to improve the performance of a fuel cell is to operate the system at its maximum allowed temperature. At higher-temperature, the electrochemical activities increase, and the reaction takes place at a higher rate, which in turn increases the power output. On the other hand, operating temperature affects the maximum theoretical voltage at which a fuel cell can operate. Higher temperature corresponds to lower theoretical maximum voltage and lower theoretical efficiency. Temperature in the cell also influences cell humidity which significantly influences membrane ionic conductivity. Therefore, temperature has an indirect effect on the cell performance through its impact on the membrane water content. The durability of the membrane electrolyte is another barrier for higher-temperature operation due to performance degradation during long-term operation. Scientists analyzed electrochemical performances as a function of the temperature distribution.

2 Analytical Simulation Model of PEM FC Stack

From the governing equations discussed before, an analytical zero-dimensional dynamic simulation model was created in Matlab Simulink environment. Topological diagram of the created simulation model can be seen in (Fig.1). The model consists of three interconnected subsystems which are responsible for simulating electrochemical, thermodynamic and mass transport effects that occur within the fuel cell stack. With this model, it’s possible to analyze the effects of ambient and operating conditions on generated output power of the used fuel cell stack in steady state and transient modes of operation [8], [11].

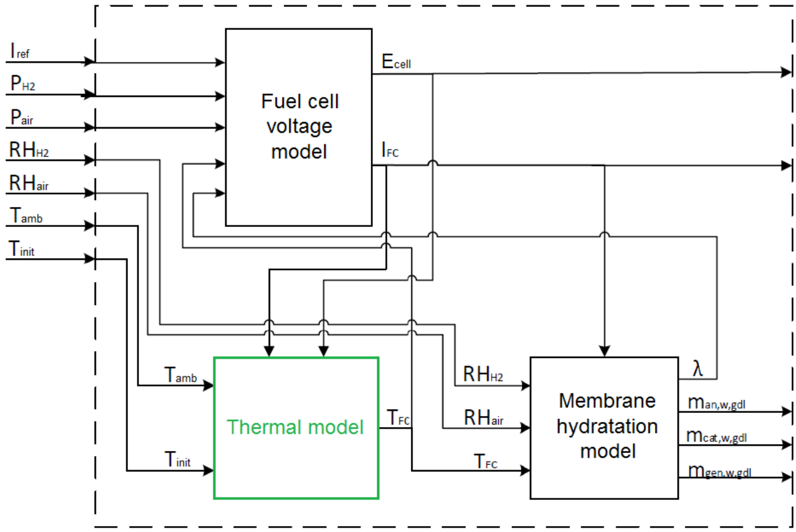

Fig.1. Topological diagram of PEM FC analytical model [8],[11].

Input parameters of the model:

I_{ref}	– load current (reference current) [A]
P_{H2}	– pressure of the hydrogen [atm]
P_{air}	– pressure of the ambient air [atm]
RH_{H2}	– relative humidity of the hydrogen [%]
RH_{air}	– relative humidity of the ambient air [%]
T_{amb}	– temperature of the ambient air [°C]
T_{init}	– initial temperature of the FCS [°C]

Output parameters of the model:

E_{cell}	– generated voltage of the fuel cell [V]
I_{FC}	– generated current of the fuel cell [A]
$m_{an,w,gdl}$	– amount of water transferred from membrane to anode GDL [l]
$m_{cat,w,gdl}$	– amount of water transferred from membrane to cathode GDL [l]
$m_{gen,w,gdl}$	– total amount of generated water [l]

Internal parameters of the model:

λ	– relative water content in the membrane [-]
T_{FC}	– actual working temperature of the FC [°C]

The focus of this paper is the thermal analysis of the PEM FC and therefore, the thermal subsystem highlighted with green color in the (Fig.1) will be further discussed in detail.

2.1 Thermal Model of PEM FC Stack

The thermal model of PEM fuel cell stack describes the changes of stack temperature depending on the ambient temperature, heat generated by occurring electrochemical reactions and the heat dissipated from the fuel cell by active or passive cooling. (Fig.2) shows the block representation of the PEM FC thermal model as a MISO system with corresponding inputs and outputs. The generated fuel cell output current I_{FC} and voltage E_{cell} which are both results from electrochemical reactions, ambient temperature T_{amb} and initial temperature of the fuel cell stack are considered as inputs to the system. The only output of the system is the fuel cell stack actual temperature T_{FC} [8], [11].

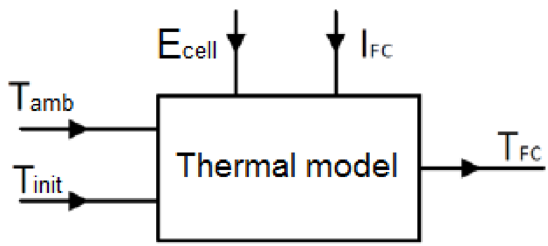

Fig.2. Block representation of PEM FC thermal model.

The transient change in fuel cell temperature can be represented by the following first order differential equation [8], [10], [11]:

$$\frac{dT_{FC}}{dt} = \frac{\Delta\dot{Q}}{M_{stack}c_{stack}}, \tag{5}$$

where $\Delta\dot{Q}$ represents a total heat flow inside the fuel cell stack [W], M_{stack} is a weight of the fuel cell stack [kg] and c_{stack} is an average heat capacity of the fuel cell stack [J/(K.kg)].

The total heat flow of the fuel cell stack can be calculated as a difference between generated and dissipated heat at any given time by equation [8]:

$$\Delta\dot{Q} = \dot{Q}_{gen} - \dot{Q}_{diss}, \tag{6}$$

where $\dot{Q}_{gen}$ is the generated heat flow [W] and $\dot{Q}_{diss}$ represents the heat dissipated from the fuel cell stack [W]. According to the forth mentioned equation, the value of the total heat flow will be positive when the temperature of the system is rising and negative when the temperature is decreasing. Its value can be also considered as a global heat gradient of the system.

The amount of generated heat flow $\dot{Q}_{gen}$ depends on the number of exothermic and endothermic electrochemical reactions occurring during the fuel cell operation as seen in [9], [10], [11].

The generated heat is causing an increase in fuel cell temperature, which in long enough time can reach values outside the operating temperature range of PEM FC. To maintain desired operating temperature of the stack, part of generated heat must be dissipated from the stack. Dissipation of heat from the considered air-cooled DEA PEM FC is caused by cooling system represented by cooling fan and by natural heat transfer mechanisms, namely convection and conduction heat transfer.

The equation of dissipated heat flow can be written as [10]:

$$\dot{Q}_{diss} = \dot{Q}_{fan} + \dot{Q}_{nat.conv}, \tag{7}$$

where $\dot{Q}_{fan}$ is a heat flow dissipated by the cooling fan [W] and $\dot{Q}_{nat.conv}$ is a heat flow dissipated from the surface of the FCs by natural convection [W]. The dissipation of heat by conduction heat transfer mechanism is not considered for the created model.

The following expression can be written for the heat flow dissipated by the cooling fan [8], [11]:

$$\dot{Q}_{fan} = \dot{m}_{air} c_{p,air} (T_{air,out} - T_{amb}), \tag{8}$$

where $\dot{m}_{air}$ is a mass flow rate of air [kg/s], $c_{p,air}$ is a specific heat capacity of the air [J/(K.kg)], $T_{air,out}$ is a temperature of the air exiting the cathode channels [°C]. The mass flow rate of air is generally dependent on stechiometry coefficient of the air and generated output power of the FCS.

Since there is no temperature regulation implemented in the model, the air mass flow rate $\dot{m}_{air}$ will be considered constant and its value is given by the amount of air flowing into system through the cooling fan [10], [11]. For the used PEM FC and other small fuel cells (FCs), it can be assumed that the temperature of exiting cathode air $T_{air,out}$ is equal to the actual fuel cell temperature T_{FC} [11].

Heat flow dissipated by means of the natural convection from the FCS surface is given by following relation [8], [11]:

$$\dot{Q}_{nat.conv} = \alpha_{conv} A_{stack} (T_S - T_{amb}), \tag{9}$$

where α_{conv} is a coefficient of convection [W/(K.m^2)], A_{stack} is the outer surface area of the FCs [m^2] and T_S represents the temperature of the surface area [°C], which is in considered model, equal to FCs actual temperature T_{FC}. For laminar flow of air, the convection coefficient for heat transfer from fuel cell stack surface to the ambient air reaches values from 5 to 10 W/(K.m^2) [11].

3 Complete Simulation Model

The complete simulation model of the thermal subsystem which was created utilizing the equations (5) - (9) can be seen in (Fig.3). Values of the required constants of the model are summarized in (Tab.1).

Table 1. Simulation parameters of the model.

Sign	Name	Value	Unit
M_{stack}	Weight of the FCs	0.25	[kg]
C_{stack}	Average heat capacity of FCs	50	[J/(K.kg)]
E_{Nernst}	Theoretical (Nernst) voltage of PEM FC	1.229	[V]
$\dot{m}_{air}$	Mass flow rate of air	4	[g/s]
$c_{p,air}$	Specific heat capacity of air	1004	[J/(K.kg)]
T_{amb}	Temperature of ambient air	25	[°C]
T_{init}	Initial temperature of FCs	25	[°C]
α_{conv}	Coefficient of natural convection	7	[W/(K.m^2)]
A_{stack}	Outer surface area of FCs	42	[cm^2]

In order to validate the performance of the created thermal simulation model, theoretical values were compared with the experimental data obtained from real fuel cell stack. The main part of the experimental work station was a commercial air – cooled PEM fuel cell stack HORIZON H – 12.

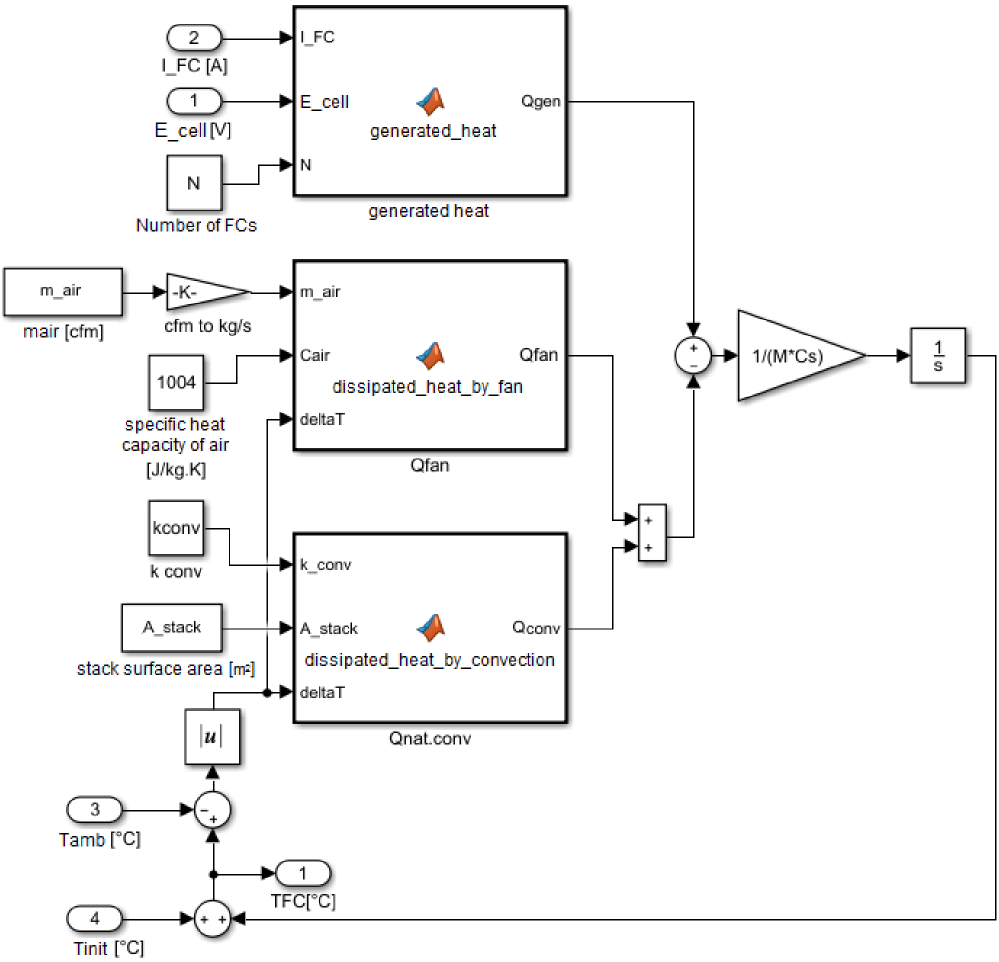

Fig.3. Simulation model – thermal subsystem.

4 Simulation Results and Discussion

With validated simulation model we proceeded to analyze the effects of temperature variations on fuel cell performance. The complex effect of temperature on FC losses can be seen on the polarization curves in (Fig.4). On the other hand, the higher temperature causes an increase in FC voltage in higher current densities. This is caused by the fact that the effect of lowering ohmic losses is more significant than the negligible increase in concentration losses. Since the peak power operating point also falls into the region of high current densities, increasing the temperature also rises the overall power output of the FCs which can be seen in (Fig.5).

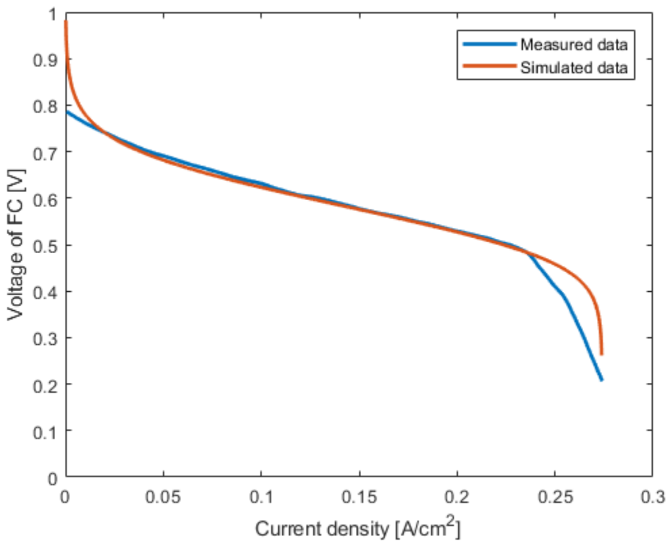

Fig.4. The effect of temperature on the character of polarization curve.

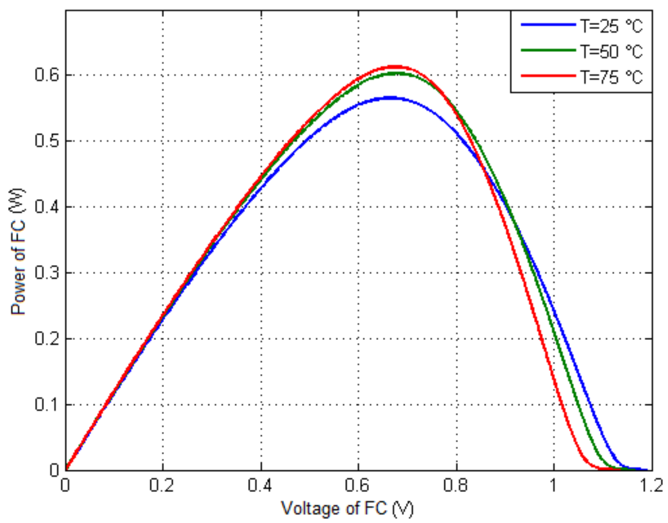

Fig.5. The effect of temperature on the value of one stack power.

The biggest change is achieved in the region of maximum peak power at voltages from 0.6 to 0.8V. Increase in the maximum power of the PEM FC is limited by the boiling point of water. Efficiency of the FC is also influenced by temperature.

On the contrary, in the region of high current densities, the efficiency of the stack increases. This is caused by shifting of the maximum power operating point towards higher values of current density and voltage.

In order to analyse dynamical properties of temperature and heat flow of the created thermal model, we carried out simulation of a transient response of FC the heat flow and temperature to the dynamic changes of generated electrical power.

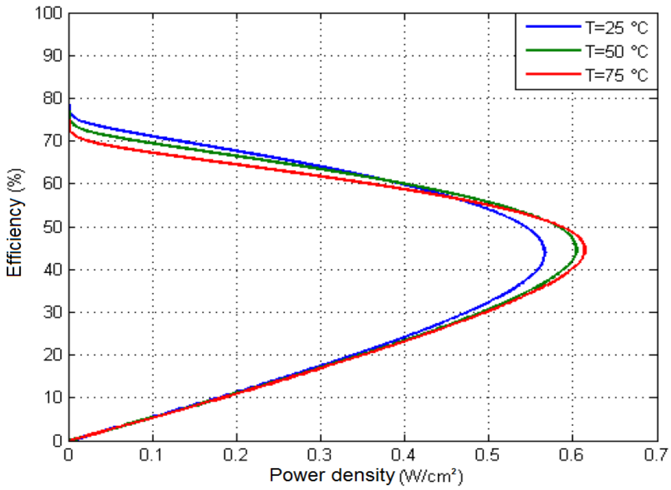

Fig.6. Efficiency of the FC as a function of power density.

Conclusion

For the purpose of analysing the effects of temperature on various parameters of PEM FCs in steady state and transient conditions without a need of experiments, an analytical zero-dimensional dynamic model was developed and validated to experimental data. The model is able to simulate electrochemical, thermodynamic and mass transport properties of the FCs. Regarding the scope of this paper, only thermal model was discussed in detail.

Efficiency of the stack exhibits a decrease in value at low current densities and increase at high current densities when the temperature rises. The maximum output power to temperature relation proved that the optimal temperature range for obtaining maximum power for the used PEM FCs is 60-80°C.

In our future work we will explore the influence of heat generation on water production and humidity inside the FCs which are highly interconnected effects.

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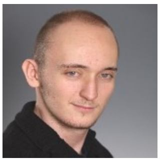

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SMART FACTORY IN INDUSTRY 4.0

Zuzana Képešiová, Štefan Kozák

Abstract:

Through the last few decades a humanity was encountering many challenges and succeed in fast technological development. As a trend continues, we are facing more and more new problems to overcome. A core of technology advancement lies within a field of manufacturing where several key aspects are combined in one: information and communication technologies, automation, mechatronics and robotics. All these pieces of puzzle are developing through time and offering us new methodologies such as Cyber-physical systems, Internet of Things and Industrial Internet of Things, Digital twin, Big Data, Cloud computing, Digital Factory and last but not least Artificial intelligence know as AI. These concepts are interconnecting in an emerging paradigm known as Industry 4.0. The paper presents the state-of-art in research and development of new information a communications technology, control techniques with use of AI, control structures and their applications in industrial processes with the emphasis on new trends stated in Industry 4.0.

Keywords:

Industry 4.0, smart factory, cyber-physical systems, IIoT, digital twin, artificial intelligence, big data, cloud computing.

ACM Computing Classification System:

Information systems, Information systems applications, Process control systems.

Introduction

Technology has become an essential part of human society. Its purpose is to increase comfort and make our daily lives more efficient. We are already largely influenced by them. In modern society, it is almost impossible to find a member without a connection to technology. Over time, technology has steadily improved and is progressing. As humanity, we have gone through several industrial revolutions, and Industry 4.0, which is being formed in current time, is the next step in the development of manufacturing.

The fourth industrial revolution brings automation of production processes to a new level by introducing customized and flexible production technologies. This means that machines will work independently or collaborate with people to create a customer-oriented production environment that constantly works on its own maintenance. Rather, the machine becomes an independent entity that can collect, analyse and evaluate data. To ensure such vision to come true, a progressive manufacturing must focus on significant challenges as sustainability, flexibility and performance of production. A promise of achievement of vision of so-called Digital factory or Smart factory is a driving force and main movement towards future of manufacturing. A large-scale change in current industrial manufacturing are inevitable and include many fields as automation, cognitive robots, digitalization, intelligent control methods and information and communication technologies. These changes open opportunities to implement different way of thinking to prototype, control process, maintain and service the Digital factory and its units.

New methods as Cyber-physical systems, Internet of Things (for Smart Factories it is Industrial Internet of Things), Digital Twin, Big Data and Cloud computing all refer to the upcoming already emerging methodology Industry 4.0.

Main aspects and characteristics of Industry 4.0 as a newest movement towards modern manufacturing is described by following key points (Kozák, Ružický, Kozáková, Štefanovič, & Kozák, 2019):

a) Interoperability – Objects, machines and people must be able to communicate through the Internet of Things, Industrial Internet of Things and Internet of Services.
b) Virtualization – Creation and visualization of virtual model resembling the real factory and its units based on real data in virtual, mixed or augmented reality.
c) Decentralization – The ability of Cyber-physical systems to work independently, to autonomously operate on sub processes based on smart decisions.
d) Real time – Ability of a Smart factory to collect data in real time, store or analyse and make decisions based on new findings is essential. This is not limited to market research but also to internal processes such as machine failure in the production line. Smart objects can identify the error and reassign tasks to other operational machines.
e) Service Oriented – People and smart devices must be able to connect efficiently via Internet of Things and Internet of Services and exchange the information.
f) Modularity – The ability of Smart Factory to adapt to new market requirements is important. Adaptation is secured by modular implementation, where hardware or software components are interconnected and easily switched.

Fig.1. Key aspects of Industry 4.0.

Individual components should be the basis for the Industry 4.0 technology model that can be applied to any production process.

The paper consists of four areas covering Cyber-physical systems, Industrial Internet of Things and Digital Twin in first chapter. Second chapter focuses on Artificial intelligence, Big Data, Cloud computing and benefits of their integration into industrial processes. Third chapter of the paper is dedicated to research and current state of implementation of Artificial intelligence in Smart factories and manufacturing processes and describes the possible directions of technology development that Artificial intelligence will affect.

1 Cyber-Physical Systems

Cyber-physical systems are the core of Industry 4.0 methodology, which interconnect other units as complex automation, cybernetic theories, mechanical engineering, design and process control, Internet of Things, Big Data, Cloud and Artificial intelligence. Thanks to Cyber-physical systems it is possible to achieve connection between human elements, machines, actuators, sensors, digital elements, embedded computers and other computational engines. Embedded computers are the main aspect of cyber-physical systems hence to their capability of highly coordinated and combined relationship between physical objects and their computational elements. (Kozák, Ružický, Kozáková, Štefanovič, & Kozák, 2019)

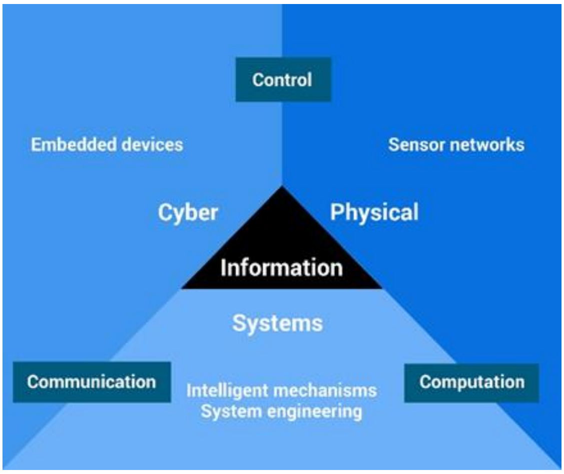

Fig.2. Principle components of cyber-physical systems.

Cyber-physical systems are considered and assumed as a system covering set of interacting physical and digital components, which may be centralised or distributed. It provides a combination of sensing, control, computation and networking functions which interwind physical objects and software to exchange information through embedded systems. A cyber-physical production system relies on the latest and further developments of computer science, information and communication technologies and manufacturing principles. A Cyber-physical system uses networked interactions which relies on physical input and output with a combination with its cyber representation consisting of control algorithms and computational functions. To achieve data about inputs and outputs a sensor plays a significant role in Cyber-physical systems.

These systems are assumed as automated to the hight extent, they are smart and collaborative ending up in optimal global behaviour in the best-case scenario. A difference of CPS and ICT lies in the ability of CPS interact and control processes with the physical world in real-time. Even thou also CPS and ICT systems process data, CPS are focused on the physical processes. Cyber-physical systems are integrating cyber space and virtual systems with real world devices, which is providing a compression of development processes by using of existing methodologies, models, techniques, tools and methods to speed up the process of custom design based on previous creations using abstract layers of design. Enough analysis in case of CPS appears as one of the most important aspects to integrate various devices, designing and modelling methods that address different aspects of the development of such systems.

A CPS structure consists of five base levels: connection, conversion, cyber, cognition, and configuration. All these five levels are based on three base methodologies of Industry 4.0 – IIoT for connection of sensors and actuators into bigger images, Digital Twin for visualizing the cyber twin in the virtual space, Big Data to handle all the information, Cloud computing for increasing the computational power and Artificial intelligence for own smart choices of maintenance and maintenance predictions.

1.1 Industrial Internet of Things

During current time, many industries across globe are moving forward to Smart factory system applying latest technologies in manufacturing field, a parts of Industry 4.0 methodology. One of these sub methodologies is also Internet of Things also known under a shortcut IoT. IoT itself is considered as an interrelated network or group of infrastructures containing interconnected objects such as sensors and actuators. These objects are parts of more complex systems as device or machine that could but also usually is not considered as a computer. These systems are considered to be “smart objects” or “smart systems” hence to their ability to generate, exchange and consume incoming data with other devices in a network for further processing such as data collection, analysis and management capabilities (Boyes, Hallaq, Cunningham, & Watson, 2018). They operate on their own without a need of human operator to intervene with such smart object. Smart objects are represented as a node in the network of smart objects, in Internet of Things, and are continuously log information about them and transmitting them to their surroundings ending up in machine-to-machine (M2M) communication.

Industrial Internet of Things is an application of IoT technology into industrial process where there are certain kinds of smart objects within cyber-physical systems used. These kinds of smart objects are set into industrial environment and are promoted for the goals of the individual industry to serve a purpose to enable real-time, autonomous and smart functioning and handling the data for optimization of whole production process including product changes and improvements, reducing the cost of production in areas such as labour costs, energy consumption, material volume and the process of manufacturing. This optimization leads into better and more accurate operation with data by machines than humans what leads into far greater speed and higher efficiency than ever before.

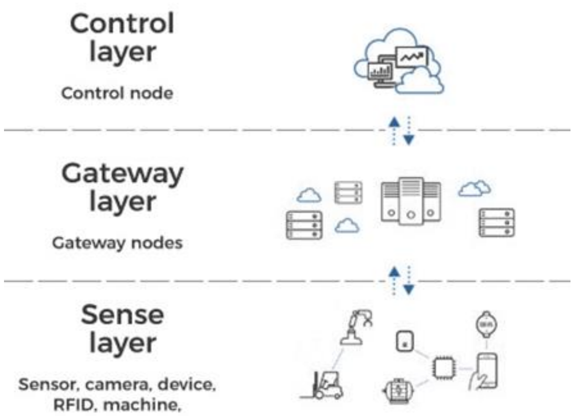

Fig.3. Three-layer architecture of IIoT.

Industrial Internet of Things is divided by (Wang K. , Wang, Sun, Guo, & Wu, 2016) into three main layers: sense layer, gateway layer and control layer.

a) Sense layer – Sensing nodes at sense layer are considered as sensors, actuators, devices or machines and are responsible for data collection about their own state and their surroundings and for data exchange with gateway layer.
b) Gateway layer – Gateway nodes are in charge for managing the data flow between Sense layer and Control layer hence their relatively high processing capabilities to run complicated routing protocol.
c) Control layer – Control nodes have job to process data from lower layers, analyse them and decide the further machine operations, which are transmitted through gateway nodes back to sense nodes, that are a part of bigger complex structure such as a machine or device capable of not only collecting the data, but also to change its behaviour.

1.2 Digital Twin

To move a Smart Factory to the higher level, a digitalization of a factory and its internal and external processes with use of virtual space is making a Smart Factory also a Digital Factory capable of visualizing processes remotely and its supporting a better understanding of production procedures and more effectively conceptualize and change the factory and its units behaviour. To ensure such technology, a Digital Twin is utilized.

A digital twin in its original form is described as a digital construction of information about a physical system created as an entity as such and associated with a given physical system. Digital representation should optimally include all system related information that could potentially be obtained by control of a physical device.

The main feature of digital twin is the ability to provide various information in a consistent format. Digital twins are more than just pure data, they contain algorithms that describe their true counterpart and decide on steps in the production system based on these processed data.

Based on the definitions of Digital Twins in any context, it would be possible to identify a common understanding of Digital Twins as digital equivalents of physical objects. Within these definitions, the Digital Model, Digital Shadow and Digital Twin are often synonymous. However, these definitions differ with the level of data integration between physical and digital associates and they could by divided into three categories based on the integration level (Kritzinger, Karner, Traar, Henjes, & Sihn, 2018):

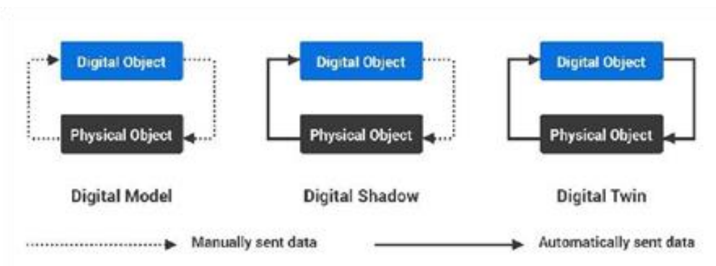

Fig.4. Digital Twin by the level of integration.

Digital Model is a digital representation of an existing or proposed physical object that does not use any form of automatic data exchange between a physical object and a digital object. A virtual interpretation may contain a complex description of a physical object. Digital data of existing physical systems can still be used to develop such models, but all data exchange is done manually and there is no automatic data exchange supported.

Digital Shadow is defined as the Digital Model capable of one-way automatic data flow between a physical object and a digital object. The automatic flow of information goes from a physical object to a digital object. This means that each physical object change is automatically projected into its digital model.

Digital Twin is a digital object that automatically displays not only physical model changes, but also changes the digital model automatically to physical level, making the digital object not only a mirror of the physical object but also its control unit.

With the growing deployment of the Internet, the concept of the digital version of every physical thing has gained its importance in industrial area as well.

2 Artificial Intelligence in Industry 4.0

A system's ability to correctly interpret external data, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation is called artificial intelligence. Artificial intelligence is a set of algorithms and learning techniques to try to mimic human behaviour. Such as image recognition, data interpretation or prediction of development of certain events like assumed time of needed maintenance of a machine, control and regulation of a machine run and behaviour.

Machine learning is one of proposed soft computing methods used for learning the machine to perform efficiently and up to date. Artificial intelligence could be applied on basically every aspect of life, whenever it comes to healthcare, finances, entertainment industry or manufacturing, technology development, automotive or industry. To achieve such accomplishments, a machine must be thought how to process the data. There are three main types of machine learning distinguished: supervised, unsupervised and reinforcement. In case of supervised learning a machine is thought to categorize provided data based on the labels, to predict a development of the tracked event, optimize the process or detect objects or anomalies. For unsupervised learning a machine is thought to group and cluster provided data by their character and content and the last type, reinforcement learning, is used for real-time decisions, navigation or skill acquisition (Sun, Liu, & Yue, 2019).

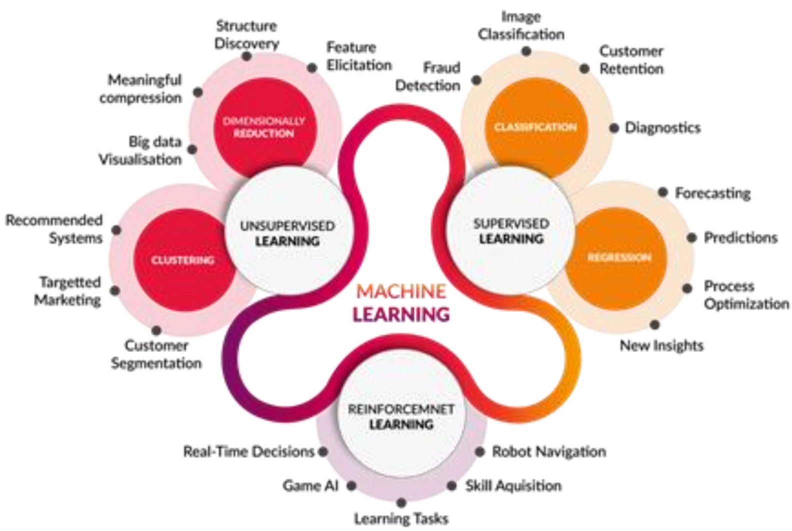

Fig.5. Machine learning approaches.

A basic approach how to achieve a machine to learn is to use neural network (NN). An artificial NN (ANN) is an interconnected group of nodes, inspired by a simplification of neurons in a brain. There are several architectures and techniques to apply ANN such as Convolutional neural networks for subtracting features from smallest to greatest, Recurrent neural networks for repeated events and especially Deep learning referring to multilayer neural network. All these techniques and many other assure to create a complex NNs to solve difficult problems to overcome many complex challenges.

Despite of Artificial intelligence being proposed several decades ago, its popularity raised up drastically only in past few years. Due to a significant improvement in computational power and networking field a computational task that took several months before, now takes only several hours. To develop a functional and fast algorithm addressing hardly achievable solutions for certain problematics having enough data and computational power is inevitable. Ensuring enormous amount of data and secure their processing capabilities new players come into game of Industry 4.0 – Big Data and Cloud.

2.1 Big Data

A term Big data does not refer to the volume of data, but to the analytics of data. Since the IoT became a popular trend in the not only everyday life of a person, but also a part of industrial part, a great amount of data started to be generated by all kinds of sensors and devices. A great number of datasets and their volume became no longer processable by conventional analytic software and new approaches had to be established. Analytics of data are more focused on revealing hidden patterns, relationships between data and other valuable business information. A deeper analysis of various data from devices, machines and processes can discover a critical parameters with the greatest impact on quality of the manufactured product as well as the speed the production process and amount of required components or materials (Zhong, Xu, Klotz, & Newman, 2017).

2.2 Cloud computing

A Cloud computing is considered to be a network of resources available on demand in a required size what evokes a higher interest of business owners due to the scalability of provided resources and their price. Cloud computing services are offering manipulation, configuration and access to hardware and software resources online. Access to the scalable resources based on cloud computing is served and released with ease and with minimum interaction required with the service provider. A cloud model consists of five essential characteristics: on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service (Zhong, Xu, Klotz, & Newman, 2017).

a) On-demand self-service – A consumer can adjust a computational resource by himself automatically without interaction with the provider.
b) Broad network access – An Access to the service is provided from standard devices such as smartphones, laptops, PCs etc.
c) Resource pooling – Computational resources of provider are clustering to serve more consumers with dynamic allocation of physical and virtual resources.
d) Rapid elasticity –The available possibilities are secured and released automatically, and they are changing on-demand. These possibilities may seem without limitations.
e) Measured service – Cloud services are automatically controlling and optimizing the resource providing based on traffic.

With the application of appropriate middleware, a Cloud computing service can handle the same tasks as any other computer in shorter time.

3 Smart Manufacturing in Industry 4.0

A technological evolution allowed industrialism to move forward by taking huge steps one at the time and resulted in current era of Industry 4.0. A core idea of Industry 4.0 is to apply autonomous methods to every possible aspect of manufacturing process and create a heterogenic environment capable of interconnection on homogenic plane, creating a Smart Factory. Independent behaviour and M2M interaction can assure more efficient, faster, cheaper and more scalable manufacturing processes. For converting a factory to Smart factory, a spirit of autonomous decision making must be blown into it, an Artificial intelligence. To fulfil the vision of a Smart factory there are several areas one can dive into. From smart design, smart machining, smart monitoring, smart control, smart scheduling to application in industrial applications. From the bottom to the top. When we address smart designing we talk about shifting design to the virtual plane with a use of virtual reality and augmented reality to serve a purpose of better understandings of physical objects and processes by not only modelling them, but also testing them, accessing them, evaluating them and controlling them virtually or remotely in later stages. Smart machining refers to real-time sensing and interacting capability of robots and objects to ensure synchronization of real devices with their digital twins to provide insight of the current situation and pass it to smart controllers to make decisions. Smart monitoring talks about not only about connecting all smart robots, devices and sensors but also about the widely spread implementation to capture the current state efficiently and from many different aspects to conclude in complex understanding of the situation. Smart control is achievable by applying cyber-physical systems into production to secure adaptive production control in real-time. Smart control is mainly executed to manage physical devices via cloud-enabled services accessible from multiple platforms such as PCs, laptops, smartphones or tablets. Having an autonomously running factory is a feature managed by smart scheduling. Smart scheduling enhances data-driven techniques to evaluate and plan the future actions of physical machines based on the provided data with the minimum cost required (Zheng, et al., 2017).

Many different aspects of Smart Factories and Industry 4.0 components were already successfully applied whenever in theoretical plane or in real life application as shown in Table 1. Movement towards Industry 4.0 trend is visible in countries from Europe, Asia and America, from small industrial countries to the biggest ones. Industry 4.0 is inevitable, and a society is adapting the new paradigm and approach to improve manufacturing processes. Industry 4.0 methodologies are available to apply not only to the manufacturing processes but also on other aspects of life in society such as healthcare, business, entertainment or government. This flexibility in field of use also provides insight into elasticity of algorithms to wide range use inside of these processes and securing even wider range of use and possible interconnection.

Table 1. Application of Smart Factory and its subcomponents by methodology Industry 4.0 .

Application	**Objective**	**Improvement**
Cross-Domain Internet of Things Application Development: M3 Framework and Evaluation, Ireland and France (Gyrard, Datta, Bonnet, & Boudaoud, 2015)	- Machine-to-machine measurement framework	- Cross-domain connection - Improved performance
Energy management based on Internet of Things: practices and framework for adoption in production management, Italy and Spain (Shrouf & Miragliotta, 2015)	- Proposes IoT-based energy management in production - Provides a framework to support the integration of energy data gathered in real-time into production management	- Integrated energy data management - Improved energy efficiency - Enhanced energy data analysis

Real-time information capturing and integration framework of the internet of manufacturing things, China (Zhang, et al., 2014)	- Provides a new paradigm of IoT to manufacturing - Designs a real-time manufac turing information integration service	- Real-time information capture - Improved logistics
Implementing a real-time cyber-physical system test bed in RTDS and OPNET, USA and Canada (Chen, Butler-Purry, Goulart, & Kundur, 2014)	- CPS test bed implemented in RTDS and OPNET	- Providing a realistic cyber-physical testing environment in real time
Enabling cyber–physical systems with machine–to–machine technologies, China (Wan, et al., 2013)	- CPS safety and efficiency	- Improvement M2M to CPS
A collaborative and integrated platform to support distributed manufacturing system using a service-oriented approach based on cloud computing paradigm, Iran (Valilai & Houshmand, 2013)	- Distributed manufacturing collaboration and data integrity - XMLAYMOD platform for distributed manufacturing agents based on cloud computing	- Upgrading the XMLAYMOD procedures and structures
Cloud Computing for Power System Simulations at ISO New England—Experiences and Challenges, USA (Ma , Luo , & Litvinov, 2016)	- Cloud computing-based power system simulation	- Higher computational power without cost of cyber security nor data privacy
Intelligent predictive maintenance control using augmented reality, Slovakia (Kostoláni, Murín , & Kozák, 2019)	- Development and deployment of maintenance system with HoloLens	- Increased quality of mainte nance processes and failure prediction - Reduction of unexpected production stops
A manufacturing big data solution for active preventive maintenance, China, Saudi Arabia and Sweden (Wan, et al., 2017)	- Propose of collection of manu facturing Big Data for prevention maintenance	- Real-time and offline prediction and analysis
Wireless Big Data Computing in Smart Grid, China, Russia and Norway (Wang K. , et al., 2017)	- Propose of wireless Big Data computing architecture	- Optimization for daily energy scheduling
Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies, Mexico, Sweden, USA and Germany (Romero, et al., 2016)	- Presentation of concept so-called Operator 4.0 for work oriented on collaboration with robots and work aid by machines	- advanced human-machine interaction technologies - automation towards achieving human-automation symbiosis work systems
Development of a Smart Cyber-Physical Manufacturing System in the Industry 4.0 Context, Vietnam and Korea (Tran, Park, Nguyen, & Hoang, 2019)	- Propose of Model of Smart manufacturing - Implementation of a Model in testbed and on real machine	- Improvement of intelligent and autonomous behaviour of components in flexible manu facturing system

Conclusion

There is visible and catchable movement towards use of modern methods such as Cyber-physical systems, IoT, Digital twins, Artificial intelligence, Big Data and Cloud computing in manufacturing and the growth of newest industrial era Industry 4.0.

Through the past few decades, computational power and networking of all sorts of devices across the smallest units as sensors and actuators to the large multiprocessor computers and group of such computers that interconnect each other a significant upturn of evolution rate was encountered. As a high demand of computational power and well networking is need by such technology as artificial intelligence, nowadays it is no problem to successfully deploy this technological method in industrial area with satisfactory results. Artificial intelligence, as it is shown in previous chapter, could not only to equal a human being in performance but overpass it in short time to the great extent. Nevertheless, there are still many opportunities and a lot of space for growth in field of artificial intelligence in industrial and manufacturing area and certainly has a great potential to improve the manufacturing process.

Acknowledgement

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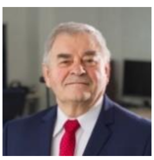

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DIGITIZATION OF EVENT SYSTEMS IN AUGMENTED REALITY USING INTELLIGENT TECHNOLOGIES

Filip Žemla, Ján Cigánek

Abstract:

We are at the brink of the 4th Industrial Revolution, in the implementation period of new information technologies into production. One such available technology is the augmented reality in the manufacturing process. The aim of this paper is to design and implement a data monitor and control of electronic devices in the production process using augmented reality. The work will employ Industry 4.0 standards. Technologies such as cloud computing, augmented reality, web applications and industrial communication protocols will be used. The presented work briefly characterizes the current situation and trends in terms of building Industry 4.0 with a focus on monitoring and control of event systems using the latest digital technologies. It describes the basic concept and structure of the proposed solution and the implementation procedure for the selected case study.

Keywords:

Augmented reality, PLC, Unity, Manufacturing process, Industry 4.0 .

ACM Computing Classification System:

Information systems, Information systems applications, Process control systems.

Introduction

We are entering a new industrial era, with the 4th Industrial Revolution (Industry 4.0) many new information technologies are coming and their interconnections. Just as in previous industrial revolutions, the driving force was the use of steam, electricity, or automation, so today the Internet and the interconnection of devices play a major role. Thanks to higher performance and smaller hardware dimensions, we can create intelligent devices for various purposes. This makes it possible to capture various process data in production, thus creating a large amount of data. To process such a large amount of data, it is necessary to ensure a sufficient hardware system, which allows the use of cloud technologies that allow us to create a digital production environment.

The work will deal with the implementation of Industry 4.0 standards into mechatronic systems in the production process. To begin with, we will look at the history of industrial production up to the current state and trends in Industry 4.0. Next, we will deal with the Internet of Things, which means the connection of all devices, objects and people with the Internet. Another important technology of Industry 4.0 is Cloud computing, which uses the Internet to store and manage data on remote servers.

1 Industry 4.0

The current state of the industrial revolution, the fourth level, is carried in the context of the term "Industry 4.0", which is already cooperating with the latest technological innovations. We were able to meet this deadline already in 2011 in Germany, when it was used in connection with changes in the field of information technology automation [1, 2].

The concept of **Industry 4.0** can also be seen as a milestone in three aspects such as smart plant, smart logistics and smart manufacturing. The smart plant is developed from a digital factory and is a key component for smart infrastructure in the future. It emphasizes the overall layout of the factory where we include production processes, systems and network distribution. (Fig.1) represents the integration itself between the mentioned aspects. Smart production is primarily related to logistics and its management. It connects with human-machine interactions (HMI) or applications of 3D / 4D technologies used in industrial processes. Smart Manufacturing cooperates through the use of the efficiency of logistics resources by supply and demand, in order to obtain services corresponding to logistics support. All three aspects are independent of each other, but together they form a coordinated production system Industry 4.0 [1, 2].

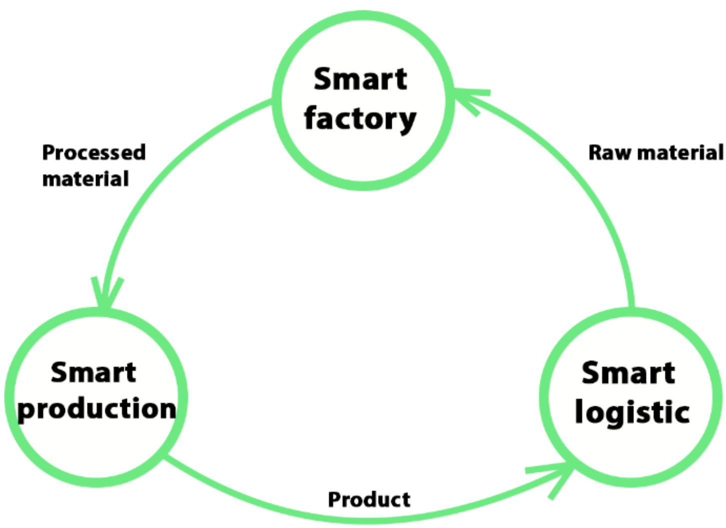

Fig.1. Key aspects of Industry 4.0 .

One of the key features of Industry 4.0 is the use of **cloud computing**. It is a technology that uses the Internet to store and manage data on remote servers. This technology provides access to data via an Internet connection [3].

The Internet of Things (**IoT**) is another key feature of Industry 4.0. It can be defined as the interconnection of computing devices, digital or mechanical machines, people, animals and objects equipped with certain identifiers (UIDs), which have a unique ability to transfer data without the need for human interaction [4].

2 Modern Technologies in Production

The work deals with the implementation of several elements of the new industrial revolution Industry 4.0 in the production process. This implementation consists of several steps using different technologies. Therefore, in this chapter we will describe the individual technologies that will be used in our design for the selected case study.

PLC devices

The basic building blocks of the new industrial revolution are PLC devices. These PLC devices are used to automate production lines and machines, collect data and then send it to HMI panels and the main computer. They can receive data that can be used to control the production line remotely [5].

Visualization systems

Visualization systems are responsible for consistent data display. All data must be sufficiently visible in compliance with ergonomic rules and psychological requirements. This means that the work environment in which the data is displayed must be configured and customized to the user. We implement visualization systems through SCADA applications. SCADA applications are adapted for data collection and control of the whole object from one monitoring point [6].

3D engines

Recently, augmented reality has also been used for data visualization, where game engines are entering the scene, which are constantly improving. There are countless game engines on the market. Two major competitors, Unity and Unreal Engine, are considered to be among the most widespread. Both game engines have been around for a long time as video game development platforms, which has added support for augmented reality game development. With the advent of augmented reality in the industry, these game engines also began to be used for data visualization in the industrial environment [7].

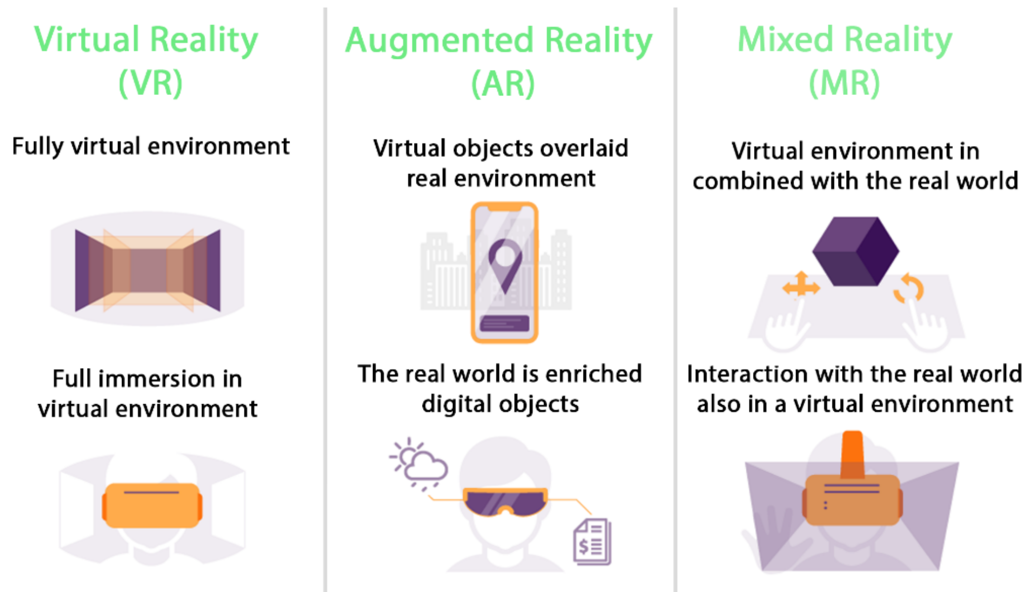

Fig.2. Comparison of VR, AR and MR.

Augmented reality XR

XR is further divided into 3 types of real estate: mixed reality MR, augmented reality AR and virtual reality VR. We could easily present a comparison of individual computer-generated properties on an example in which the user opens the door.

In virtual reality, the user would see virtual doors in the computer generated reality that he could open. In augmented reality, the user would see doors from the physical world that would wear "door" in computer-generated reality.

In a mixed reality, the user would see a physical door that would have a virtual button next to it. In contrast to augmented reality, the difference would be that when the button was pressed, a signal would be sent to the engine on the door and the physical door would open. In addition, mixed reality has interactivity with the physical world [8].

Cloud platforms

The term cloud platform refers to a package of applications, services, hardware, and the operating system of a server in an Internet data center. The cloud platform allows organizations to create, manage, test and back up products, as well as offer data analysis or video and audio streaming. In recent years, we have seen increased interest in cloud platforms and an increase in their use. Due to the high interest, many cloud platforms have emerged, of which we list the 3 largest and most used [9]:

- Amazon AWS
- Microsoft Azure
- Google cloud
- Technology frontend

Frontend development is the area of web application development that focuses on what users see on the screen. It involves the transformation of the code received from the backend (server) into a graphical interface. Like all technologies, frontend technologies are advancing and no longer require only knowledge of HTML, CSS and Javascript languages. Gradually, front-end frameworks began to grow, with their own programming languages becoming popular. Today, we already know a large number of frameworks that are used to create web applications [10].

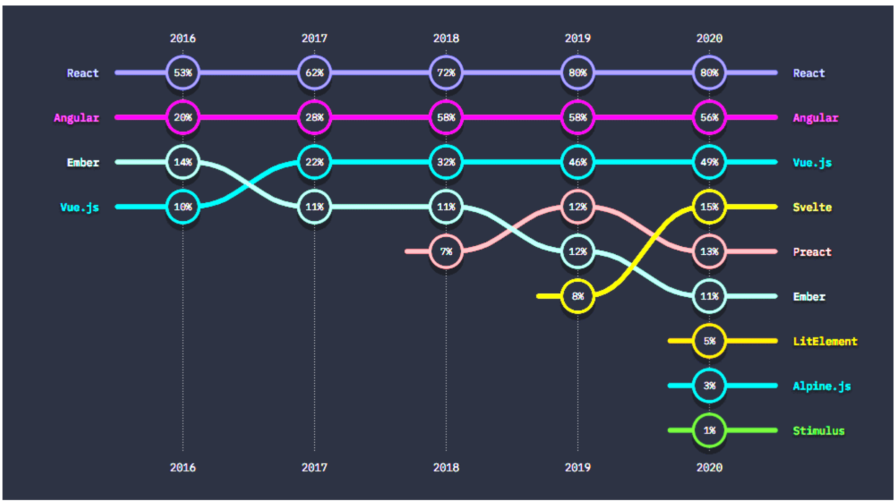

Fig.3. Frontend framework popularity chart [10].

3 Current State Analysis

We focused mainly on the results and the current state in the field of augmented reality and communication links between smart devices. We focus on the results devoted to the monitoring and control of mechatronic systems using computer-generated reality.

An important part of the analysis is to examine the possibilities of using communication technologies between smart devices, a local server and a cloud server. Thanks to this, we will be able to gain knowledge of the selection of optimal communication protocols, interfaces and also cloud technologies. One of the researched studies was a simulation factory [11]. The result of the study was the connection of a production device controlled by a PLC device to a local KEPServerEX server. Subsequently, the data was sent to the ThingWorx cloud server, from where the data was sent to the AR application. The system used two communication protocols, the Ethernet protocol and the OPC UA protocol.

Another experimental system was the P2P communications trading platform [12]. The work dealt with remote access to device data and remote device control. This project was implemented using P2P communication using the MQTT protocol. The work included two local servers, the first of which was Node-Red, which represented the position of MQTT broker. The second server provided a web user interface. After the user logged in, P2P communication with the devices was started.

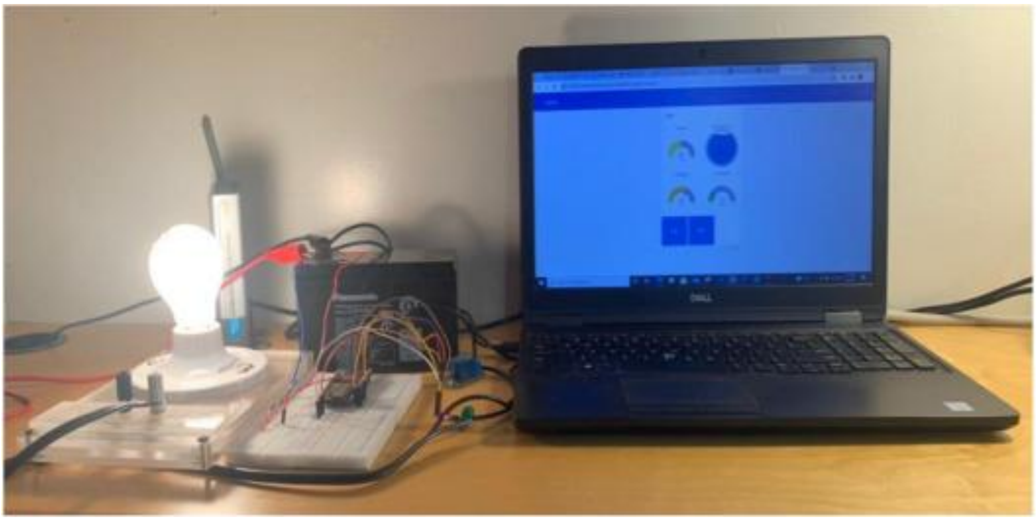

Fig.4. Experimental setup for the proposed platform.

In the next part of the analysis, we focused on the possibilities of displaying augmented reality and anchoring virtual objects in reality. The following studies have addressed this issue. The first is a project that aims to show new parts in construction using augmented reality [13]. The XR application includes the ability to add basic geometric 3D models such as cubes, cylinders, spheres, pyramids, etc. in various dimensions that the user can change. 3D models can be placed anywhere in space. The "save model" function scans the machine on which the 3D model is located. Scanning consists of shooting video while observing the machine at different angles. When the scan is complete, the video is divided into a series of images of the machine and sent to a cloud server. A machine forecast is then created on the cloud server, which the next time the machine is displayed in real-time, it recognizes the machine and allows it to add a virtual design. When you save a design, a virtual design is sent along with the video, which is sent as an array of voxels.

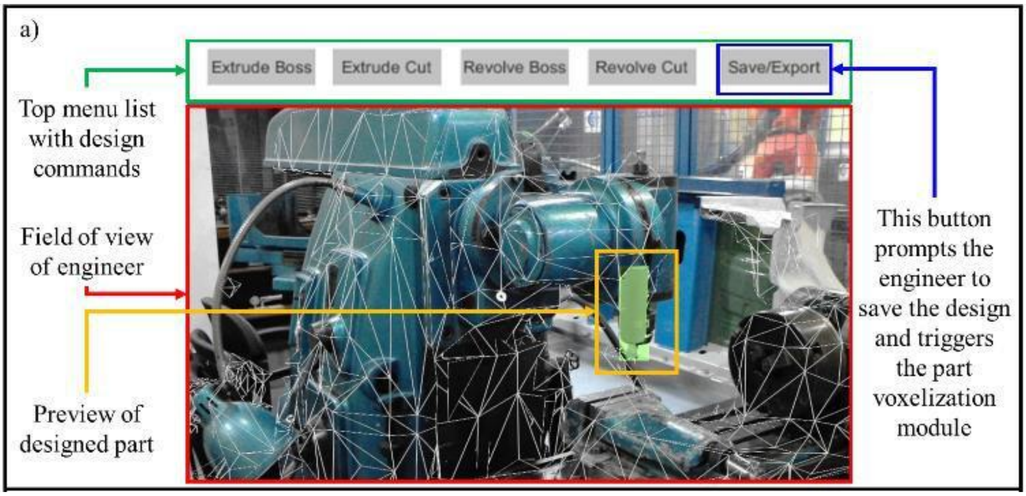

Fig.5. Augmented reality view a proposal for a new work.

Working [14] using a mobile device with an AR application allows you to display values from sensors in the device. According to the sensed values, it is possible to display a fault in the real device. In addition, the application allows you to stream the recording to other devices with an AR application or a web browser.

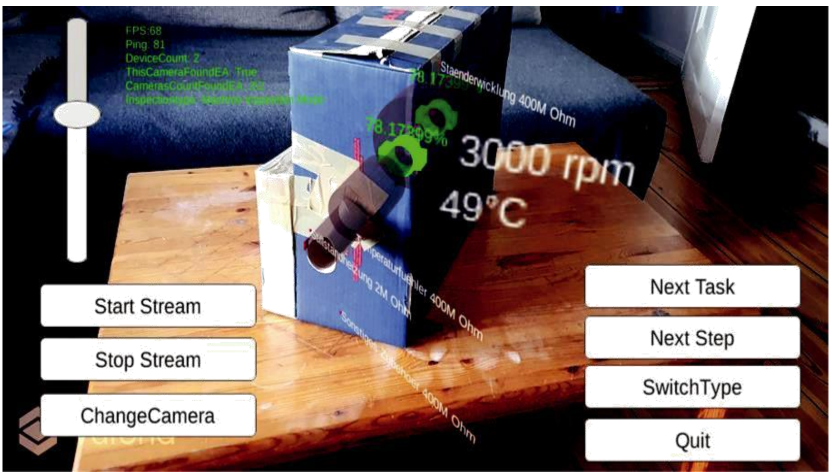

Fig.6. User interface.

Further work is Modern methods of control and monitoring of mechatronic systems using computer-generated reality [15]. The work is characterized by a combination of augmented reality, cloud technologies with Industrial Internet of Things (IIoT). The AR application was developed in the Unity 3D engine for iOS devices (iPad). Object recognition was performed using a 3D map created in Wikitude Studio. After the object was recognized, the AR application connected to the InfluxDB cloud server to a digital copy of the object. At the same time, it downloads the user interface definition from the local server, which is used to display the user interface in the 3D engine. The communication within the whole project is based on the MQTT protocol.

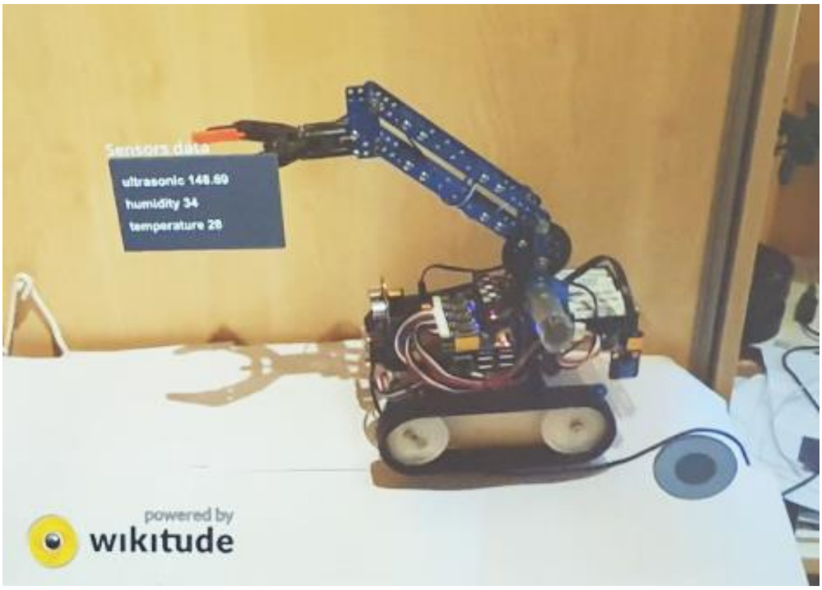

Fig.7. Augmented reality view of the device.

4 Solution Design and Implementation

Each of the examined solutions has its strengths as well as weaknesses compared to the others. The aim of this work is to design a smart workplace with data recording, backup on cloud storage, using exclusively IIoT standards in accordance with the concept of Industry 4.0 and management. It will be possible to interact with the physical system of the workplace through the application in augmented reality. A web application will be used for remote monitoring of analytical values. Based on research into the current state of use of cloud technologies and augmented reality in IIoT, we have encountered several shortcomings that can be improved:

- Communication of devices will be realized only using IIoT standards
- Dynamic display of the user environment based on the recognized device

Software and hardware selection

The first step will be to choose a suitable cloud platform. Here are a few options to choose from, the most popular of which are:

- Microsoft Azure
- Google cloud
- Amazon AWS

All options are suitable candidates for stable operation and project implementation. However, as this is an IIoT project, Microsoft Azure will be the ideal decision, as it is most associated with Industry 4.0.

Another big decision will be the choice of 3D engine. Here we have a choice of two competitors: Unity Engine and Unreal Engine. Both 3D engines were originally developed as game engines and over time began to be used in other industries. In the case of augmented reality in an industrial environment, the Unity Engine is used in most cases thanks to its support of several devices. Another advantage is that Unity has more documentation for creating AR applications. These facts make Unity Engine a clear choice for creating an AR application. Furthermore, it is necessary to appropriately select the Software Development Kit (SDK) for visualization of augmented reality. Here are some options that depend on each other for the augmented reality visualization device used:

- AR core
- AR kit
- AR Foundation
- MRTK

Before deciding which SDK will be suitable for our project, it is necessary to determine what equipment we will use to visualize augmented reality. If we opt for a mobile device, it will be ideal to use the AR Foundation, with which we can easily create a single application compatible with both iOS and Android operating systems. If we were to opt for the Microsoft Hololens 2 headset, we must choose the MRTK instruction set.

A thorough analysis revealed several possibilities for recognizing objects in the real world:

- Object recognition by position
- Object recognition by marks
- Object recognition according to the shape of the monitored object

Recognition of the object by location in our case will be inefficient, as we will only move in the room. Object recognition by tags is an effective way to recognize an object, the most common solution is to use QR codes. Nowadays, however, there is a more modern solution available in the latest versions of the SDK, namely object recognition according to the shape of the monitored object. In our case, the most effective use will be to recognize the object according to the shape of the monitored object.

Design of the solution implementation structure

We created a design for the smart workplace structure (Fig.8). The structure can be divided into several units according to the technology used.

The first part will be developed using the TIA Portal tool. In it, we program Siemens devices which include the touch panel HMI and PLC devices. We will set up communication and network settings of individual devices. The devices in this section will communicate with the local server using the OPC UA protocol.

The second part is made up of a Node-Red local server. It is a server that will be able to communicate with devices from the previous part using OPC UA communication, AR devices using MQTT protocol and a cloud server using TCP / IP protocol and MQTT. It will also provide the HMI on the appropriate port on the local network.

The third part is a cloud server. Here we chose to use the Microsoft Azure cloud platform. The cloud server will contain a database with RESTful API, to provide data to devices. The server will record hourly, daily, weekly and monthly records to provide analytical data. The server will also contain individual devices in production and their user interfaces.

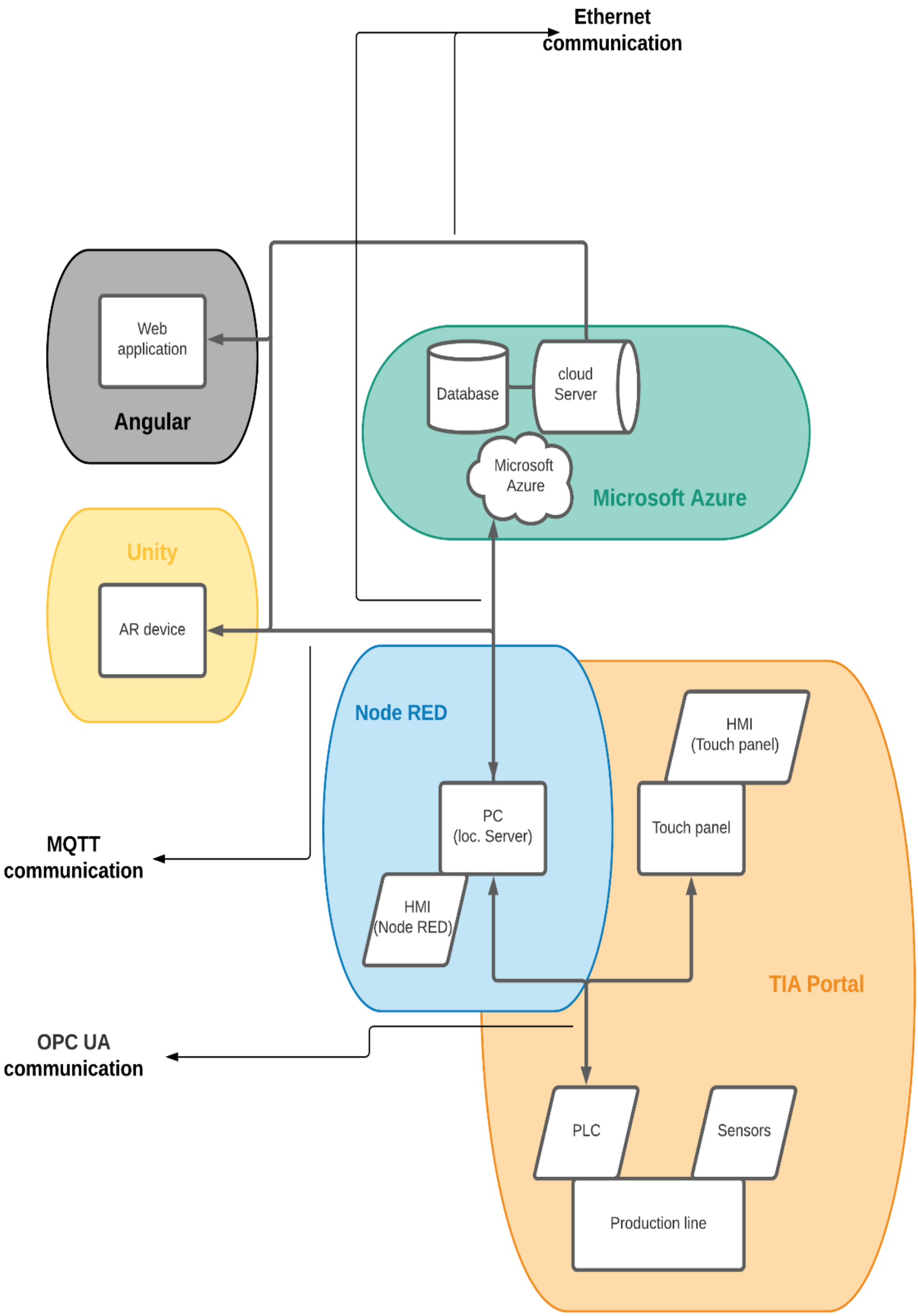

Fig.8. Solution structure design.

The fourth part is an augmented reality application that will be created in Unity Engine. The application will recognize devices in production and then provide the appropriate HMI obtained from the cloud server according to the recognized device. After recognizing the device and successfully displaying the HMI, the application will connect to the local server, from which it will obtain current device data. This communication will take place using the MQTT protocol. The application will also be able to switch to analytical mode, in which data is obtained from the cloud server.

The last part is made up of a website created in the Angular framework. The web application will provide analytical data for remote production monitoring. The security of the web application will consist of user authorization.

Utilizing augmented reality in the manufacturing process can streamline production speed, maintain machines, reduce machine downtime, and effectively provide information about the machine. Implementation of dynamic visualization, based on the display according to the data in the database by the respective machine will provide us to effectively add visualizations for new equipment in production. This eliminates the lengthy process of programming new versions of the application and allows you to easily add a new device with its visualization to the database.

Conclusion

The work deals with the implementation of augmented reality and cloud systems into the production process using Industry 4.0 standards. A significant extension is the use of 3D object recognition based on the observed object in the physical world. The system is supplemented by an algorithm for rendering the user environment based on the data received from the server in JSON format. This will make it possible to easily add new equipment by adding to its user experience and edge mapping.

The solution will be designed and verified for a specific smart system. The proposal will be based on the principles of Industry 4.0 so that the overall concept and methodology is generally applicable in accordance with industry standards.

Acknowledgement

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ROBUST EXPLICIT CONTROL OF COMPLEX HYBRID DISCRETE PROCESSES

Štefan Kozák

Abstract:

The paper deals with design of simple end effective robust explicit control of complex hybrid systems. We consider discrete hybrid systems consisting of several discrete state-space models with parametrical uncertainties. The parametric uncertainties are considered in coefficients of state space model (A) and (B). The main goal of the paper is to be proposed and verified the robust explicit hybrid control algorithms such for stable and for unstable complex dynamical systems with respect to parameter model uncertainties. Proposed robust explicit controller method is based on the iterative algorithm's computation of control law parameters for the known target polytope with respect to parameters uncertainties and constraints on state, control and output variables. For demonstration ability of the proposed methods, we verified the several examples. An example is presented to illustrate the details of the proposed robust hybrid parametric controller design. In this paper we consider hybrid dynamical model consisting of 4 state-space model with 30% uncertainties of matrix (A) coefficients. We compare obtained numerical and graphical results with solution which are obtained from very known MPT toolbox. Our proposed method solution in all cases gives a stable solution while the MPT does not guarantee the stability for tested cases. The proposed method and algorithm is convenient for application for SISO and MIMO processes.

Keywords:

Hybrid control, explicit controller, robust control, robust hybrid control, parametrical uncertainties.

ACM Computing Classification System:

Information systems, Information systems applications, Process control systems.

Introduction

Robust model predictive control (MPC) of hybrid systems is important class of constraint model based control methods that can explicitly account presence of modelling uncertainties in the controlled process. Explicit MPC is control method where MPC optimization problem is solved off-line with multiparametric programming methods. Result of this optimization is partitioning of state space into disjunct partitions each of which is assigned to function of system state. Control input is than calculated in 2 steps. First step is location of current state into one of state space partitions. Second step is evaluation of corresponding function which gives current optimal input.

In this paper we design different type of explicit controller whose intent is to supply robust control input which is probably, instead of optimal one. Proposed controller consists of set of *(m+n)* dimensional (*m* – number of system inputs, *n* – number of system states) polytopes which represent state-input space. To get robust control input we first need to locate current system state into one of state-input space polytopes. Result of slicing this polytop at values of current state is *m*-dimensional polytope which defines range of robust system inputs.

1 Structure of Model

In this article we use discrete hybrid state space models. As it is hybrid model it contains more nominal submodels with defined area of operation. Following is structure of the model:

$$\boldsymbol{x}(k+1) = A_{Ai}\boldsymbol{x}(k) + B_{Ai}\boldsymbol{u}(k)$$
$$H_i x(k) \le K_i$$

where x is real vector representing state of model,
$x \in \bigcap R_i^{\ n}$
u is real vector representing input of model,
$u \in \bigcap R_i^{\ m}$
A_{Ai} is actual real matrix of proper dimension
B_{Bi} is actual real matrix of proper dimension
R_i^n is n-dimensional state space polytope
R_i^m is m-dimensional input space polytope
H_i, K_i are matrices defining area of operation of *i*-th submodel

As we would like to propose robust hybrid control we also use parametrical uncertainties on every model parameter. Actual model parameters are then calculated as follows:

$$A_{Ai} = A_{Ni}(1 + A_{Ri}A_{Ui})$$
$$B_{Ai} = B_{Ni}(1 + B_{Ri}B_{Ui})$$

where A_{Ni}, B_{Ni} are nominal matrices A, B
A_{Ui}, B_{Ui} are matrices of uncertainties of A_{Ni}, B_{Ni}
A_{Ri}, B_{Ri} are random matrices, $A_{Ri}, B_{Ri} \in <-1, 1>$

Matrix products in these equations should be interpreted piecewise.

Thus we have defined nominal model, its uncertainties and the way how actual model is calculated from nominal model and its uncertainties. A_{Ui} and B_{Ui} define maximum possible change of nominal values in A_{Ni}, B_{Ni} respectively and A_{Ri}, B_{Ri} determine actual change. This way we get $2^{(m+n)}$ of extreme actual models - each random coefficient is set either to 1 or -1.

2 Control Algorithm Design

As model itself contains parametrical uncertainties we are not able to bring it exactly to target point. It is always necessary to define some tolerance, *n*-dimensional polytope around the target, which is accurate enough to fulfil our requests. This target polytope can be of any size bigger than 0 and have to contain target point.

We would like to propose robust control which drives system state into defined target polytope. We do not care if the control is optimal or not. In this article we would like to design iterative method for computing robust control of hybrid systems. The simplified algoritm of this process can be described as follows:

Step 1	Set the control target to defined target polytope
Step 2	Find state space and associated inputs space from which it is guaranteed to get to target polytope in one step if parametrical model uncertaities are met
Step 3	Set the target polytope to computed state space
Step 4	Go to Step 2 and repeat until explored state space is big enough

The core of the algorithm is *Step 2* which we describe in next section:

Step 2a We process one vertex of target polytope so that we make backwards simulation of particular extreme actual model (model with maximal possible uncertainty) using all combinations of inputs extremes. If we have *m* inputs we deal with 2^m of input extremes combinations and after backward simulation we get 2^m states. Backward simulation is done using this formula:

$$x(k) = A_{Ai}^{-1}\left[x(k+1) - B_{Ai}u(k)\right]$$

If we combine these states with associated inputs we get *(m+n)* dimenstional polytope. Important property of this polytope is that it contains all states from which it is possible to get to target polytop vertex in one step. Moreover if we cut this polytope at values of selected state we get accurately defined inputs which controls model into target polytope vertex. This property comes from linearity of model.

Step 2b We repeat *Step 2a* for all target polytope vertices. Thus we get new polytope which has similar property than previous one. If we cut it at values of selected state, we get range of inputs each of which controls model into target polytope. Example of such polytope for model with 2 states and one input is depicted in (Fig.1).

Now we know how to control actual model (which is derived from nominal model using one of extreme parametric uncertainties) into target polytope in one step. Solution to this problem is mentioned "states-inputs" polytope which defines states from which we are able to control model into target polytope in one step and also defines input range which can be used for every state.

Step 2c We repeat *Step 2b* for all possible parametrical uncertainties extremes and get set of similar "states-inputs" polytopes - one for each uncertainty extreme.

Conjunction of all these polytopes is again polytope (call it "partial solution" polytope) which defines all possible states which we can drive into target polytope if system meets defined model uncertainties. It also defines range of inputs which can be used to achieve this target. The mentioned polytopes conjunction is depicted in (Fig.2).

Step 2d As we are working with hybrid model which consists of linear submodels each of which is valid only on specified state space we have to trim "partial solution" polytope so that it does not exceed area of validity.

After repeating this procedure for every submodel of our hybrid model, final "solution" polytope array of *Step 2* is union of partial solution polytopes.

Very important condition is that original target polytope has to be a subset of "solution" polytope array which we get after first iteration. Otherwise we are not able to guarantee successful control. (Fig.3) shows final solution - polytopes array.

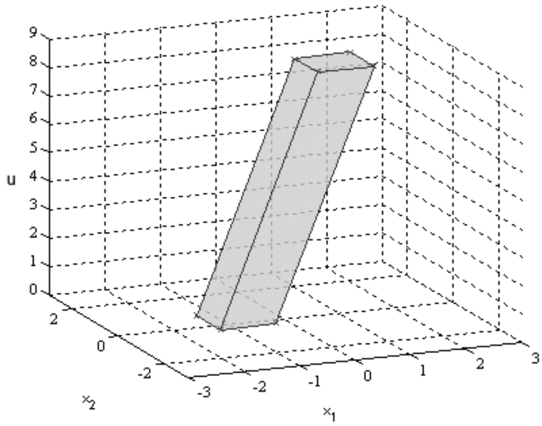

Fig.1. State-input polytope defining states from which we can control actual model into target polytope in one step. I also defines possible inputs range for particular states.

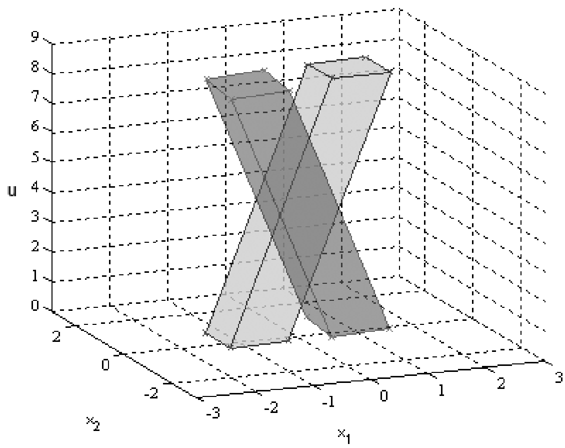

Fig.2. Conjunction of “states-inputs” polytopes.

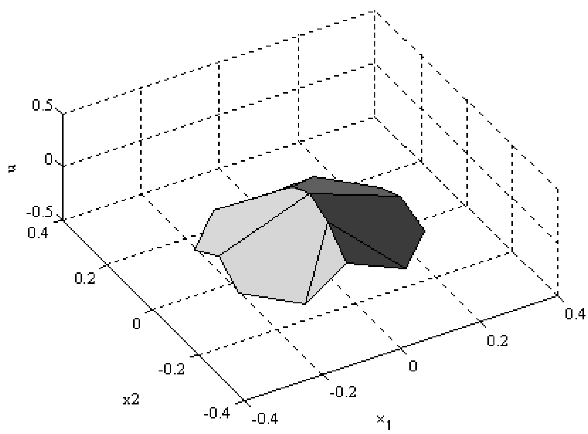

Fig.3. Solution polytopes array describing all states and corresponding inputs from which we can control model into final polytope in one step.

2.1 Control algorithm

Result of controler design is array of polytopes arrays which were created during iterations through control design algoritm. These polytopes define subset of state space for which we have defined control inputs. Let´s index these arrays based on order of iteration they were created.

First step of control is to define polytope that contains current state. We start searching from lower polytope index to higher and use first positive result. First polytope that contains current state defines also inputs range that guarantees that model state will be controlled towards target. As here we do not care about control performance we can select and implement input which meets following inequality:

$$H_i \begin{bmatrix} x_k \\ u_k \end{bmatrix} \le K_i$$

where x_k is current state of model,
u_k is real current input of model,
H_i, K_i are matrices defining area of operation of i-th controller polytope

In every next step we repeat this procedure.

3 Case Study

In this case study we design explicit controller for discrete hybrid model consisting of 4 discrete linear submodels each of which has 2 states and 1 input. The goal of control is to get system state into predefined surround of coordinate system.

Model used in the simulation is defined by following matrices:

$$A_{N1} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, B_{N1} = \begin{bmatrix} 1 \\ 0.5 \end{bmatrix}, H_1 = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}, K_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$A_{N2} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, B_{N2} = \begin{bmatrix} -1 \\ -0.5 \end{bmatrix}, H_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, K_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$A_{N3} = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix}, B_{N3} = \begin{bmatrix} -1 \\ 0.5 \end{bmatrix}, H_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, K_3 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$A_{N4} = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix}, B_{N4} = \begin{bmatrix} 1 \\ -0.5 \end{bmatrix}, H_4 = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, K_4 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Uncertainty matrices for all submodels are defined as follows:

$$A_U = \begin{bmatrix} 0.3 & 0.3 \\ 0.3 & 0.3 \end{bmatrix}, B_U = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

System input constraints were defined as follows:

$$-10 \le u \le 10$$

Target polytope is defined as follows:

$$\begin{bmatrix} 0 & -1 \\ 1 & 0 \\ 0 & 1 \\ -1 & 0 \end{bmatrix} x \le \begin{bmatrix} 0.1 \\ 0.1 \\ 0.1 \\ 0.1 \end{bmatrix}$$

After algorithm passed 20 iterations we obtained robust controler which is shown in (Fig.4).

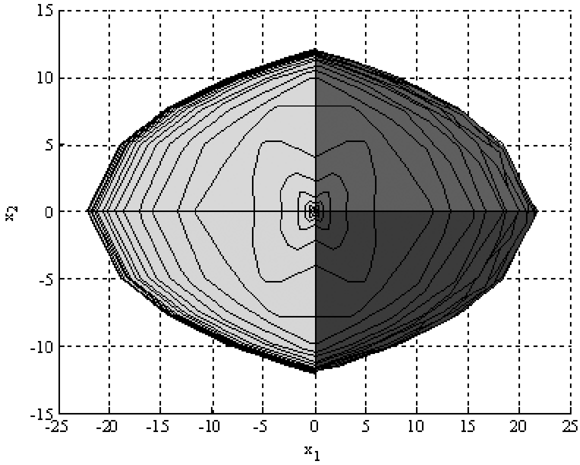

Fig.4. Partitioning of state space by explicit hybrid controller.

To simulate system control for every simulation step we have chosen different actual model based on model uncertainties. (Fig.5) shows different state trajectories based on what actual model is used in simulation, however every time system state ends in target polytope. (Fig.6) shows corresponding control inputs.

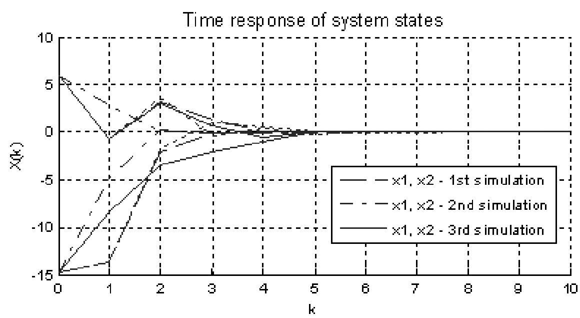

Fig.5. Different state trajectories based on actual model.

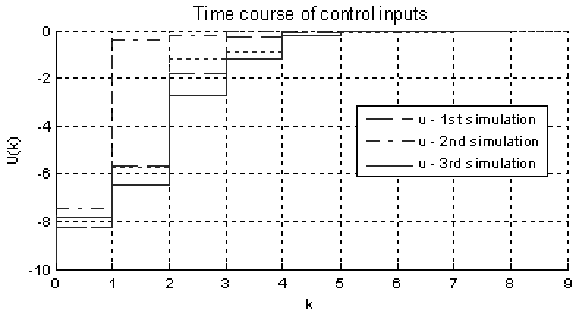

Fig.6. Different course of control inputs based on actual model.

Finally we have created optimal controller using MPT toolbox. We have created it so that it does not take into account any model uncertainties. To simulate this controller we used model with uncertainties. As expected this controller was not able to control the system from every initial state. To show difference between optimal and robust controller we selected some initial states which optimal controller was not able to control or not enough good, and made control simulation with optimal and robust controller. Results of this comparison are shown in (Fig.7) and (Fig.8).

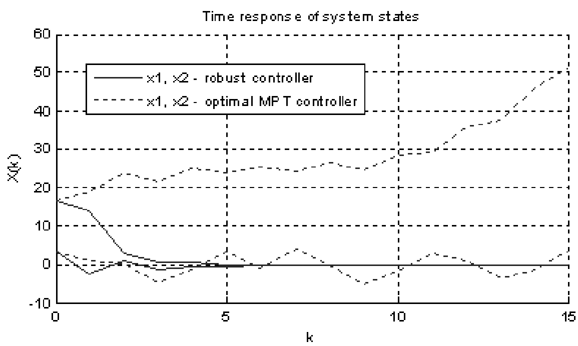

Fig.7. Comparison of state trajectories of optimal and robust controler.

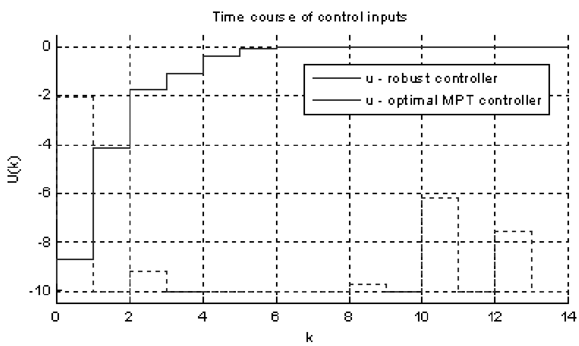

Fig.8. Comparison of control inputs of optimal and robust controler.

Conclusion

This paper deals with design of robust control for discrete hybrid systems. The main result is a proposal of explicit hybrid controller which is able to control even non-stable hybrid system to desired state with arbitrary precision bigger than 0.

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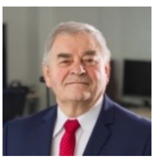

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ALGORITMS FOR ENVIRONMENT MAPS OF MOBILE ROBOT

Oto Haffner

Abstract:

Robot needs to have some representation of the environment to free of collision move. There are different types of environment maps in mobile robotics however the most used are metric maps. The aim of this work is the proposal of algorithms, for real robotic system, that can map the environment. In this work we deal with the analysis of properties of the laser scanner and the making of its model. Further a method is proposed for making map based on the properties of the scanner and program implementation of this method. The result of this work is a program that maps the environment and which is usable on real robot system.

Keywords:

Map, laser, rangefinder, environment, mapping.

ACM Computing Classification System:

Information systems, Information systems applications.

Introduction

Robot is complicated mechanical device, controlled by computer, equipped by many sensors to get information from surrounding environment and by many actuators for manipulating with objects or self manipulating. This definition is one of the many.

Robots can be sorted to more groups by their construction. Independent group are autonomous mobile robots. There must be defined word autonomous and mobile. The mobile robot is able to move and orient in unknown environment. To do this actions robot needs to know answers to three main questions: “Where am I?”, “Where I want to go?” and “How to get there?”. To get answers to these questions, robot needs somehow to sense the surrounding space.

Sensors for localization and navigation can help us to answer the previous three questions. One of the sensors for navigation is laser rangefinder with which we work in this paper and also analyze its characteristics.

To do the tasks of mobile robotics, mainly localization and navigation, it is necessary to have a representation of environment - configuration space. The main configuration spaces are geometric, topologic and metric maps. In this work we will deal with methodology of making the metric map using laser rangefinder.

1 Sensor for Navigation

One of the main activities of mobile robot is obtaining and processing of information about environment in which robot is moving. This information robot obtains thanks to different sensors.

The most used are rangefinders worked on different physical principles – ultrasonic, infrared and laser. These types of rangefinders can measure distance to measured object and also direction to this object.

1.1 Parameters of laser rangefinder HOKUYO UTM-30LX

The parameters stated by the manufacturer are defined for a surface of exact size, situated perpendicularly to the beam of measurement. In practice it is often necessary to scan various kinds of surfaces from different angles, therefore it is necessary to experimentally verify the stated parameters for different surfaces and different angles of measurement. To complete the data necessary for the creation of the sensor model three types of experiments were performed. The first was focused on the repeatability of the measurement perpendicularly to the object, the second was aimed at the repeatability of the measurement under the angle of 45° and the third was aimed to the stability of the measurement of the edge of an object. The first two tests verify the stability of the measured distance, while the third test verifies the stability of the measured angle and the measurement on the border of two objects. (Dekan et al, 2011) The surfaces of white wall, white paper, black paper, white T-shirt, aluminium foil, mirror and plexiglas were used for these tests.

1.2 Result of measurement

For each material were taken 200 measurements in predetermined distance (500mm and 1500mm) and two angles (90° and 45°). For mirror and plexiglass surface were taken additive measurements because of unclear results. From all measurement results was found some knowledge. Laser rangefinder would give bad measurements results for the material of plexiglass or glass and mirror or high polished metal surface. These facts can be compensated by the synthesis of data from the more sensors worked on different physical principle. We can also guess that the rangefinder would bad interpret materials or obstacles which are very thin or narrow e.g. wire mesh.

Because the laser rangefinder is planar, the measurement must be interpreted in plane. This is the reason why there is needed a measurement aimed at consistency of data around the edges of obstacles. That measurement was done on Institute of Control and Industrial Informatics FEI STU (Dekan et al, 2011). The measurement was taken by four distances 50 cm, 150 cm, 250 cm and 530 cm. For each distance, measurements were performed 10 times with 500 measured distances per data set. The measurement result is the number of shifts of the object for its left and right edge (Tab.1).

Table 1.

Measured distance	Number of measurement									
	1	2	3	4	5	6	7	8	9	10
50 cm	161	246	197	220	180	190	146	108	136	248
150 cm	191	27	105	211	85	90	60	31	180	33
250 cm	44	43	48	38	160	74	39	5	142	18
530 cm	5	32	34	0	42	74	14	2	1	0

Based on the Gaussian distribution and the measured distances it is possible to determine the shift of the object border on the basis of angular distances between two beams of the laser range finder (Tab.2) according to:

$$y = 3.\sigma.\sin(d).dst \tag{1}$$

where d is the angle between two consecutive laser beams and dst is the measured distance.

Table 2.

Measured distance	σ [mm]	y [mm]
50 cm	0.6078	3.9783
150 cm	0.416	8.1677
250 cm	0.2907	9.5131
530 cm	0.1269	8.802

1.3 Model of laser rangefinder

The complete sensor model consists of two partial models. Hokuyo UTM-30LX is a planar rangefinder so it measures distance in the plane. It must be interpreted in the plane.

Based on the data obtained from the measurement (Fig.2), the Gaussian sensor model was chosen. The probability distribution of measured distances in the Gaussian model equal to:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2}$$

where σ is the standard deviation and μ is the average distance of measurements. For partial model in the direction of measuring distance was Gauss distribution determined as average standard deviation from all type of measurement. The value is σ = 4,9391. The resulting Gaussian distribution is in (Fig.2).

As the model is in the direction perpendicular to the direction of distance measurements, the model derived from the shift of object boundaries was chosen. The resulting standard deviation for the Gaussian distribution in this direction was σ = 3mm. The resulting distribution can be seen in (Fig.3) (Dekan et al, 2011).

Based on these two resultant Gaussian distributions the resulting model of laser range finder has been created (Fig.4):

$$f(x,y) = \frac{1}{2\pi\sqrt{\sigma_x^2\sigma_y^2}} e^{-\left(\frac{(x-\mu_x)^2}{2\sigma_x^2}+\frac{(y-\mu_y)^2}{2\sigma_y^2}\right)} \tag{3}$$

where x is the corresponding measured distance, the σ_x is standard deviation of the Gaussian distribution in the direction of the measured distance, y is the corresponding dispersion distance in a direction perpendicular to the measured distance and σ_y is the standard deviation of the Gaussian distribution in the direction perpendicular to the measured distance.

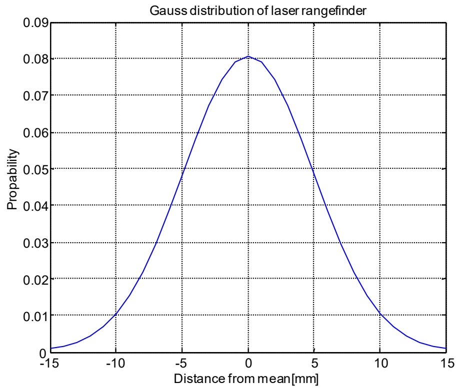

Fig.1. Gauss distribution of laser rangefinder for x direction.

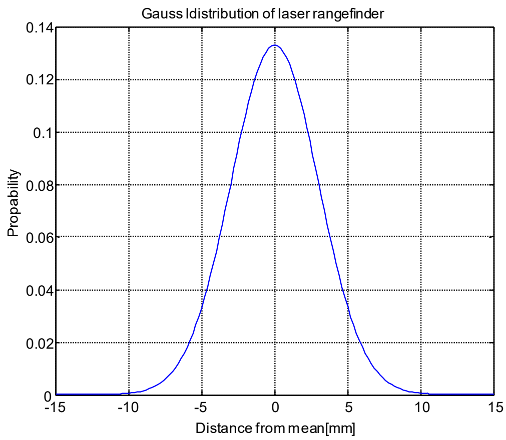

Fig.2. Gauss distribution of laser rangefinder for y direction.

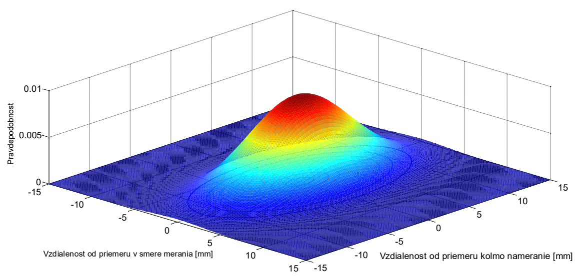

Fig.3. Final model of laser rangefinder. Left coordinate: distance from mean in x direction, Right coordinate: distance from mean in y direction. Elevation: probability.

For purposes of mobile robotic can be model of laser rangefinder be given in form of table. For the selected raster 10x10mm is table (Tab.3), where the number in the cell represents probability of occupancy.

Table 3.

0.0074	0.1397	0.0074
0.0329	0.6228	0.0329
0.0074	0.1397	0.0074

2 Map Making Method

For the best representation of environment using laser rangefinder was chosen a metric map. This map uses grid with cells. In our case, the cells are represented by pixels in map. It is easy to determine the occupancy of each pixel.

At first, it was necessary to design a procedure thanks to data from laser which can be potted to map. The principle we describe on (Fig.5).

The method of making local map is needed. Let us based on the assumption that the initial position of robot is **[x0, y0]**. There is known distance **r** and angle **α** for each measured point. We must work with fact that the angel of first measured point is set to 45°. Each next measurement has the angel smaller for 0.25°(angle step) respectively for angel 0.25 * index_measurement. With this fact is worked in the calculation of the resulting angle. As well we must work with orientation of the coordinate system. In this case we do not work with rotation of robot yet. On the base of mentioned facts, we can define the coordinates of measured points as:

$$x=x_0+r*\cos(45°-0,25*index\_measurement)$$
$$y=y_0+r*\sin(45°-0,25*index\_measurement) \qquad (4)$$

where x, y is coordinates of measured point, x_0,y_0 is initial robot position, r is measured distance and *index_measurement* is analogical index of measured point (1-1080).

Robot changes its position and rotation during mapping. We must work with this fact in correction of equations. Also the initial coordinates and robot rotation must be set. Initial rotation angle can be set as 0°. Counter clockwise robot rotating adds to overall rotation angle, anticlockwise robot rotation subtract from overall rotation angle. The problem is how to set the initial robot coordinates in map. Wrong set can cause problems during plotting. With this problem we will deal later. Let us suppose that the robot coordinates can have also negative value but this is not possible in plotting to map.

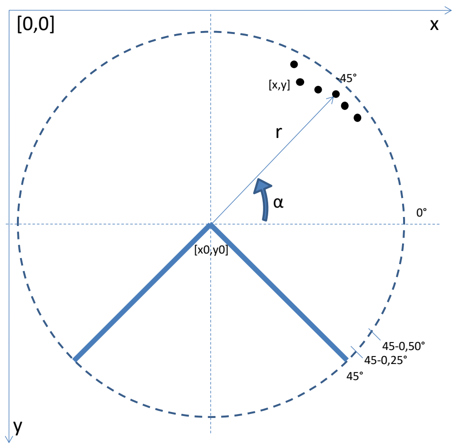

Fig.4. Method sketch.

The coordinates of point for making global map are defined as:

$$x=(x_0+x_r)+r*cos(45°-0,25*index\_measur-\varphi_r)$$
$$y=(y_0-y_r)+r*sin(45°-0,25*index\_measur-\varphi_r) \quad (5)$$

where x,y are coordinates of measured point in the image matrix, x_0,y_0 is initial robot position in coordinate system of image matrix, r is measured distance, *index_measur* is index of measured point, x_r,y_r are robot coordinates in robot coordinate system, φ_r is overall rotation of robot considering the axe y_r.

Philosophy of the relationship of rotation angle and coordinate system of image matrix is for better understanding shown in (Fig.6).

The main idea of making global map is plotting local maps in each coordinates where each map was measured. The main task is to set correct position (coordinates) and correct rotation angle in coordinate system of image matrix.

The main idea of making global map is plotting local maps in each coordinates where each map was measured. The main task is to set correct position (coordinates) and correct rotation angle in coordinate system of image matrix.

The main problem is alignment local robot coordinate system in global coordinate system of environment map (image matrix). However this work does not deal with problems of robot localization.

3 Program Realisation

After making of sensor model (section 1) and method of map making (section 2) we can do a program realisation. Because program codes for laser rangefinder UTM-30LX are for operating system Linux and also the mobile robotic system in FEI STU work under this operating system, we decides to use operating system Linux-Ubuntu 12.04 . For working with images was used library OpenCV 2.4 which is a library of programming functions mainly aimed at real-time computer vision (Bradski and Aguado, 2008). The resulting program is a console application.

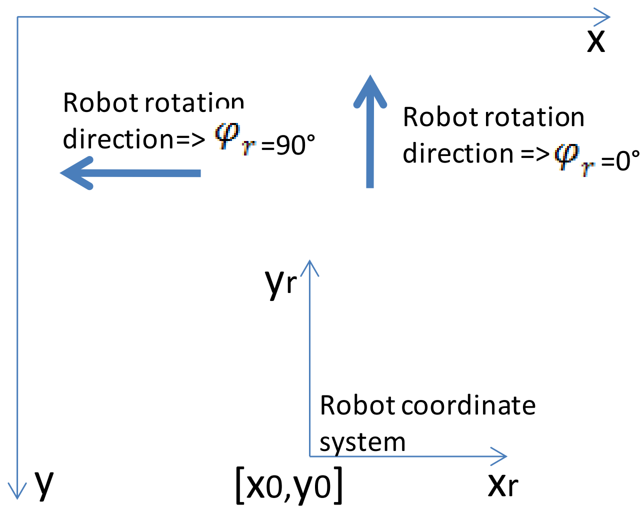

Fig.5. Coordinate system of picture matrix.

3.1 Local map

For making local map we need this information: measured data, robot position, map scale. Measured data from laser scanner are saved in text file, each measure on its own line. From structure like this is easy to connect one measure with measure angle. Distances are measured in millimeters. It must be set the map scale and robot initial position before plotting the map. Orientation and robot coordinate system is shown on (Fig.5). By the equation (5) (section 2) can be calculated position of measured data in the image (map). For simplicity, in the early stages of making maps we will not use sensor model.

For making of first local map was created artificial environment for paper boxes (Fig.6 - left). The distance of paper box from laser was less than 600 mm so the size of image matrix was set to 1000 x 1000 pixels with scale 1:1 (1 pixel = 1 mm). The position of laser in map was experimentally set as [500, 800]. The resulting map we can see on (Fig.6 - right). In this case the neighbouring measured points were connected with segment.

3.2 Global map

To make a global map we need this information: measured data, actual position and rotation of robot, initial position and rotation in map, scale.

For making a global map was created artificial environment from paper boxes which simulate real robot environment (Fig.8).

In this environment 21 measurements were done. For each measurement was remembered the position of laser and a total rotation angle.

Fig.6. Artificially made environment (left) and its local map (right).

Fig.7. Artificially made environment for global map.

Each measurement is saved in text file. Position and robot angle are saved in one text file. The structure of data is: X position, Y position, Angle. Metric unit of position is centimeter and angle decimal degree. The robot position is not position in map but position in robot coordinate system (section 2). There can be a situation that the map size is too small and some data would not be plotted. That is the reason why there is a scale. The scale has an effect on the robot coordinates. The resulting equations for measured point with scale are:

$$x=(x_0+x_r*10/SCALE)+r/SCALE* \\ *\cos(45°-0{,}25*index\_measur -\varphi_r)$$

$$y=(y_0-y_r*10/SCALE)+r/SCALE* \\ *\sin(45°-0{,}25*index\_measur -\varphi_r) \quad (6)$$

where x,y is position of point in coordinate system of image matrix, x_0,y_0 is initial position of robot in coordinate system of map, r is measured distance, *index_measur* is index of measured point, x_r,y_r is position in coordinate system of robot, φ_r is total robot rotation considering the axe y_r, *SCALE* is our set scale.

3.3 Map plotting 1

First way of making map was connecting the center of laser and plotted point with segment. Resulting map we can see in (Fig.8).

Disadvantage of this way is that the data and borders plotted in the image are redrawn. In (Fig.8) we can see how measured data overlap the image size. This is caused only by missing obstacle. The white color changed to violet is only for illustration. In (Fig.9) is demonstrated partial drawing of the map.

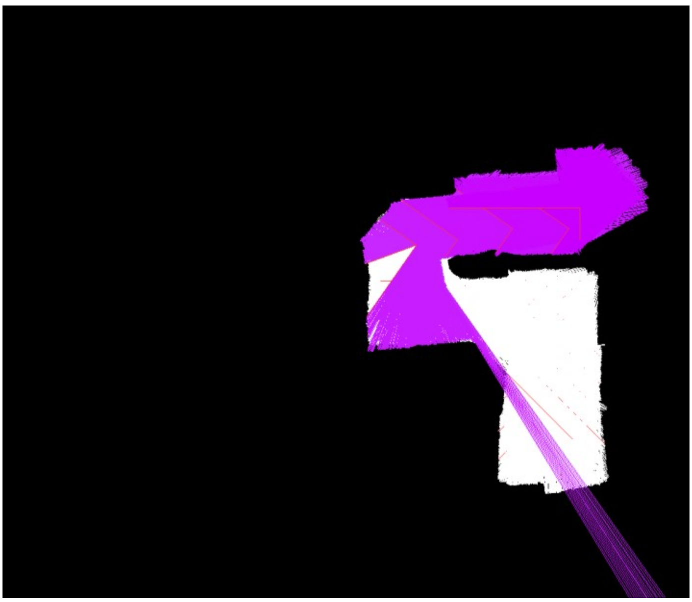

Fig.8. Global map drawn by first way.

Fig.9. Partial drawing of map.

3.4 Map plotting 2

We tried to improve previous way of making map by setting the brightness level of segment between center of laser and measured point to one level- white color and the measured point to another- black color. Resulting map we can see in (Fig.10).

The border of map was not highlighted by another brightness level and that is the reason why they were overlapped. The border is better to see in this map however the data are still redrawn and it cause map distortion. In (Fig.11) we can see partial drawing of map.

3.5 Map plotting 3

In this way we decided to not draw the segment connecting the center of laser and measured point. Only the measured point is drawn. Resulting map we can see in (Fig.12).

In previous way of making map we highlighted the borders of map however some part of border was redrawn due to position error. In this map we can see each point measured by the laser. In the upper part of map we can see the imperfection. This was caused by the wrong determining of laser position. In (Fig.13) is demonstrated partial drawing of map.

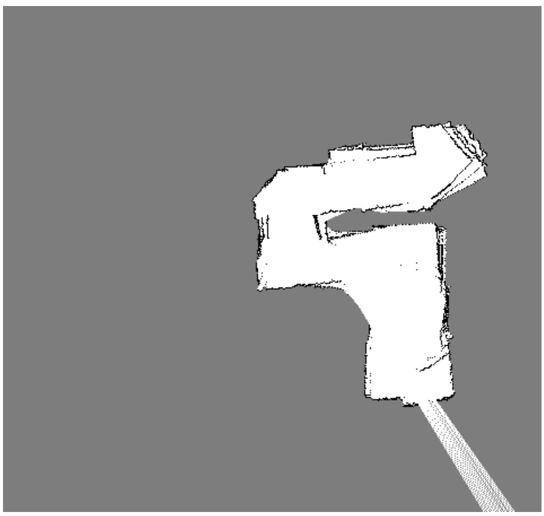

Fig.10. Global map drawn by second way.

Fig.11. Partial drawing of map.

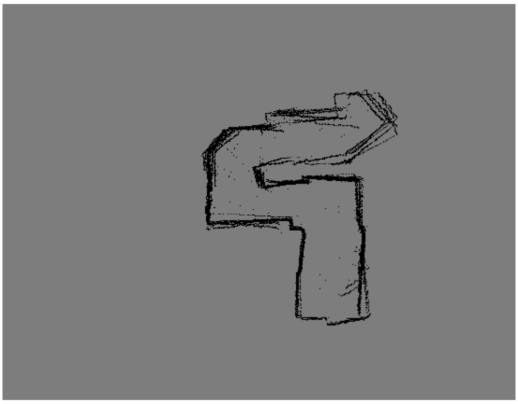

Fig.12. Global map drawn by third way.

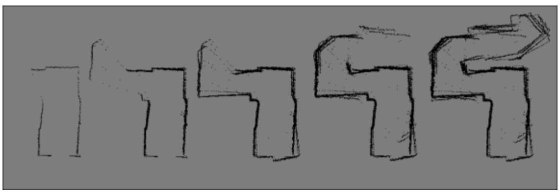

Fig.13. Partial drawing of map.

3.6 Map plotting 4

We tried to improve the previous way of making map. The main idea is that the drawn points can obtain more brightness level. If the measurement falls in the pixel for the first time, the pixel obtains the upper set brightness level. If the measurement falls in the pixel again, the pixel brightness is lover for set level. This is repeated until the pixel has the lover brightness level- black color. Resulting map, where 3 brightness levels are set, we can see in (Fig.14)

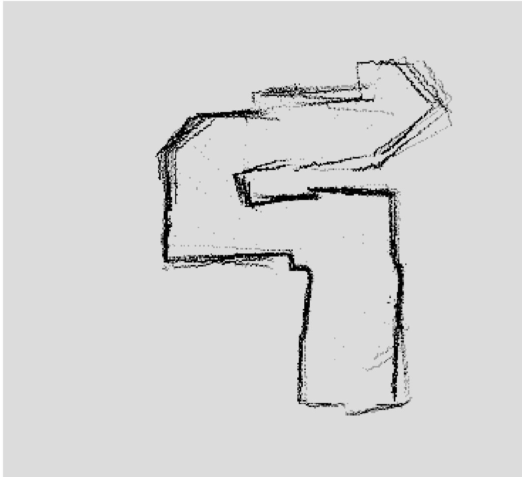

Fig.14. Global map drawn by fourth way.

After thresholding this map we can delete the points with lover brightness level. Less number of measurements fell on these pixels. The less number could cause error of measurement or odometry error but also moving obstacle. The partial drawing of map is in (Fig.15).

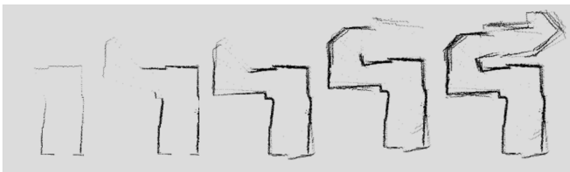

Fig.15. Partial drawing of map.

3.7 Editing resulting map

As the final way of making map was chosen the last (fourth) way. This map needs thresholding (Fig.16) because it contains pixels which have different brightness level.

On the map is applied binary threshold. The pixels with brightness level higher than 160 (set by us), obtain after thresholding maximal brightness (gray color) and all other the minimal (black color). This threshold level was set because if in the point fell 3 measurements (5 possible), we consider this point as occupied. The level of threshold depends on number of brightness level, which can obtain one pixel, but also on the obstacle speed and size. To set the brightness level we did not have enough data, that is the why we only suggest the using of thresholding.

As we can see in (Fig.16), the border of map is not clean and straight. We apply on the map advanced algorithms of image processing. We apply the dilation algorithm which cause "thickening" of border (Fig.17). This algorithm will cause that the distorted map border is filled. In this case the core size is 5 pixels and has circular shape.

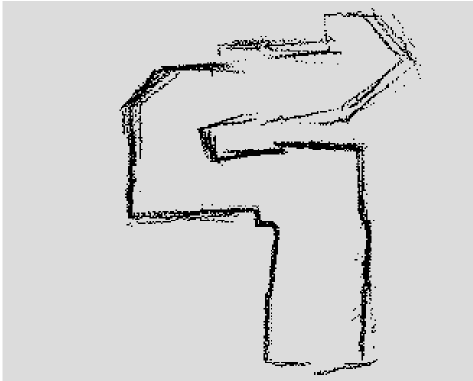

Fig.16. Thresholded global map.

Fig.17. Map after dilation.

After application of dilation the following algorithm was erode. This algorithm cause that the borders will be thinner (Fig.18). In our case the core size was 4 pixels and the rectangular shape. Using bigger core caused deleting the thinnest lines.

For purposes of global navigation or localization would be sufficient map with borders or lines thick 1 pixel. The thickness of borders in previous maps does not determine the thickness of obstacle. This thickness is caused only by measurement error. This is the reason why we applied the skeletonization algorithm (Fig.19). The core of this algorithm is distance transformation.

The result of the algorithm is the map skeleton but it contains some unneeded disturbing segments and points. This is the reason why we tried to improve process of editing map. The background brightness level was set to 255 (white color). In process of erode and dilate was the core set to circular shape and size to 7 pixels. The erode filter was used 2 times a row and after this the filter of dilate was used (Fig.18).

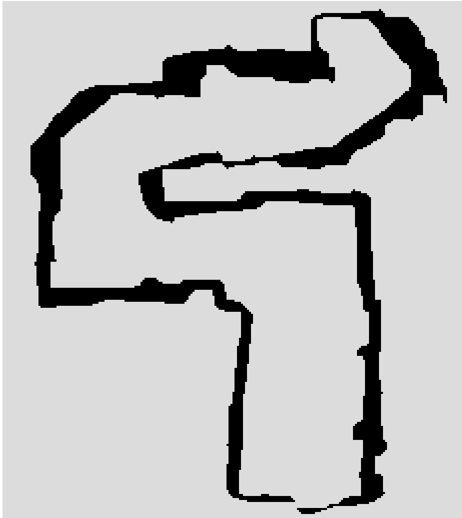

Fig.18. Map after erode.

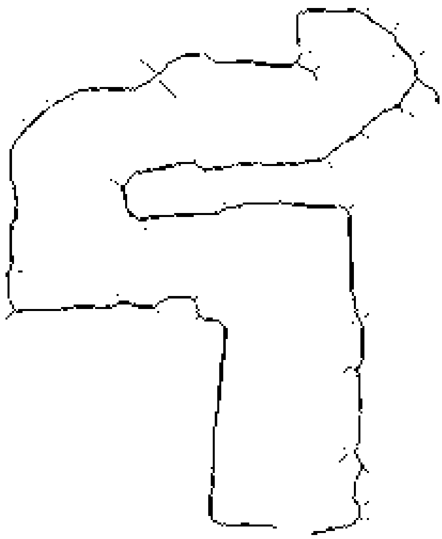

Fig.19. Map after skeleton algorithm.

The result of the algorithm is the map skeleton but it contains some unneeded disturbing segments and points. This is the reason why we tried to improve process of editing map. The background brightness level was set to 255 (white color). In process of erode and dilate was the core set to circular shape and size to 7 pixels. The erode filter was used 2 times a row and after this the filter of dilate was used (Fig.20).

On the filtered map was used Gauss smoothing algorithm and binary thresholding. Gauss filer cause blurring of map borders and their smoothness. The sharp roughness are softened after the thresholding.

On edited map was used Zhang-Sueng thinning algorithm. The resulting figure we can see on (Fig.21). By applying filters and thinning algorithm we get required result. The small disadvantage is that the sharp corners ale rounded now however this does not make problems in tasks of global navigation.

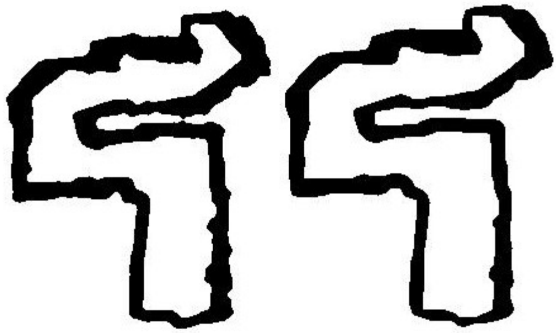

Fig.20. Map after double erode a one dilation (left)
and after gauss smooth fiter and thresholding (right).

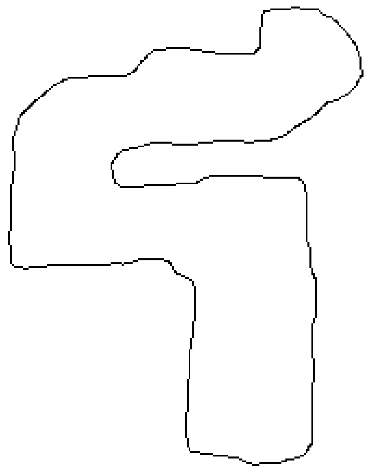

Fig.21. Skeleton of map after using of Zhang-Suen algorithm.

Conclusion

We could met some problems in application of the algorithms of making map.

Map scale

The problem with right setting of scale depends on the environment size that robot is to map. The scale of map could be set manually if the robot operator knows what environment is to be mapped. If the robot is to map building with size of 20 x 20 meters and the map will be 1000 x 1000 pixels the scale could by theoretically set to 1:20. In this case, the initial coordinates of drawing the map have to be set ideally to not exceed the border of image.

Here comes the problem how to set the right initial coordinates. One of the solutions can be oversizing the scale. However in this case the map could be drawn very little in view of size of image matrix. Too high scale can cause higher error in global navigation. Next solution can by adaptive adjustment of scale (Fig.22).

We can determine the position of all point that are to be drawn. If the coordinate fall in to the pixel out of the map matrix, the map will be redrawn in other scale again. Now the pixels will fall in to the new image matrix. This way can be ensured that the map will have the same size and all the flat will be used.

Map using

Primary using of our map will be global navigation thus finding of way between start and finish. Metric global map can be used for making of topological or geometric map. This map will use robot.

However, global map can use also the human. There can be situations where human needs information about size and shape of environment e.g. building where human cannot go by himself. In this case the map can be use for visualization of unknown environment. Global map contains also the metrics so we can compute the content of area.

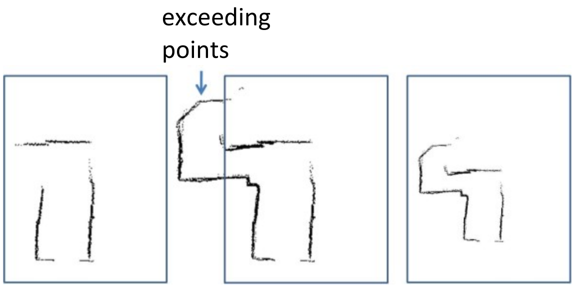

Fig.22. Initial map (left), exceeding points (middle), adapted scale (right).

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