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CONTENTS – SPIS TREŚCI

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USING STEALTH TECHNOLOGIES IN MOBILE ROBOTIC COMPLEXES AND METHODS OF DETECTION OF LOW-SIGHTED OBJECTS

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Abstract. *The paper outlines the latest technologies used by the world's leading manufacturers in the development of mobile low-observable robotic systems and promising measures to improve the quality of components and design of such objects. Methods of detecting objects using stealth technologies are considered, and it is shown that only due to a system approach it is possible to compensate for the reduction of the effective scattering surface of low-observable objects by technical means of radar stations. It is shown that the main method of increasing the range to the radio horizont is the use of an air-based radar. Methods of detecting objects on the traces of their interaction with the environment are promising for organization of cooperation of several radars in the detection of low-observable objects.*

Keywords: stealth technologies, mobile robotic complex, low-observable object, radar station, detection methods, signal-to-noise ratio

WYKORZYSTANIE TECHNOLOGII STEALTH W MOBILNYCH ZESPOŁACH ROBOTYCZNYCH ORAZ METODY WYKRYWANIA NIEWIDOCZNYCH OBIEKTÓW

Streszczenie*. W artykule przedstawiono najnowsze technologie stosowane przez wiodących światowych producentów w rozwoju mobilnych systemów robotycznych o niskiej obserwowalności oraz obiecujące działania mające na celu poprawę jakości komponentów i konstrukcji takich obiektów. Rozważono metody wykrywania obiektów wykorzystujące technologie stealth i wykazano, że tylko dzięki podejściu systemowemu możliwa jest kompensacja zmniejszenia efektywnej powierzchni rozpraszania obiektów słabo obserwowalnych przez stacje radarowe. Wykazano, że główną metodą zwiększenia zasięgu do poziomu radiowego jest użycie radaru lotniczego. Metody wykrywania obiektów na podstawie śladów ich interakcji z otoczeniem są obiecujące w wykrywaniu obiektów słabo obserwowalnych przy współpracy kilku radarów.*

Słowa kluczowe: technologie stealth, mobilny kompleks robotów, obiekt niepozorny, stacja radiolokacyjna, metody detekcji, stosunek sygnału do szumu

Introduction

Stealth technologies are a complex of technical solutions; their application reduces the level of signals from an object to receiving devices of an object detection system. The stealth technologies are effectively used in objects that belong to the class of low-observable objects. Designing the low-observable objects is the result of a scientific and technological breakthrough in expensive scientific and highly efficient technologies and is the property of mostly economically highly developed countries, whose doctrines are based on a guaranteed military and technical superiority over other countries.

1. Main directions of using and designing the low-observable means

Nowadays, there are three main directions in aircraft, shipbuilding, mechanical engineering and mobile robotics of applying low-observable means [18]:

- the maximum possible introduction of stealth technologies for objects to be constructed and designed;
- application of single "invisibility" elements, caused by the lack of sufficient funding (in most cases, the anti-radar coverage and some other elements of full-fledged stealth technology are rejected);
- design and manufacture of small low-observable means (mobile robots), which can be utilized for operating on enemy's territory.

Main scientific and technical directions of modern stealth technologies are a theory of diffraction on complex objects and production and investigation of radiation-absorbent materials. Development of stealth technology begins with a mathematical modeling of electromagnetic wave scattering on an object whose radar visibility is to be reduced. This stage is essential for preliminary evaluation of a possible result and allows optimizing a shape and electrophysical characteristics of the object. Mathematical models are based on the boundary value problems for the electromagnetic wave diffraction on objects of complex shape, which include special materials. A modern computer technique allows creating software to simulate the electromagnetic wave scattering on complex objects like aircrafts and ships, regarding a large number of equipment, cracks, hatches and other details. Such modeling yields an architecture of the object with shapes that satisfy the invisibility conditions. A low visibility of the object can be achieved by choosing the architecture due to the fact that a radar signal, like a light ray, propagates in a straight line according to the geometric optics laws. This means that the object architecture must be chosen to prevent the signal reflection in the direction of the radar receiving antenna caused by the reflection in other directions. Dimensions of signal reflection surfaces must be much larger than the wavelength of a radar signal, this provides its reflection from a mobile object surface. The radar signal scattered on the whole surface must be formed in a special way in order to place the instantaneous equivalent center of the object out of its geometric dimensions. This complicates the radio-locating steering when attacking a mobile object.

2. Creation of the newest materials for MR cases

A crucial factor in invisibility is the material of the MR case. Leading research laboratories create substances and materials with specified properties of real and imaginary parts of the dielectric constant in a required frequency range. However, similar studies in the creation of substances with the given law of magnetic permeability change in a certain frequency range are difficult in practical implementation.

Emergence of mobile robotic complexes (MRCs) with a wide range of action required the creation of new materials and technologies of their production for implementation in created samples of MRCs [12].

Development of the MRCs is one of the key priorities for technical modernization of the country's military. New materials and production technologies for development of new models of MRCs promote technical modernization and updating of manufacturing.

In development of electromagnetic wave absorbers, various materials are used having a property of absorbing electromagnetic radiation in a certain frequency range. The ability of a medium to absorb electromagnetic radiation is determined by its electrical and magnetic properties, namely the specific electrical conductivity and dielectric and magnetic permeability. These characteristics are used to describe a process of electromagnetic wave propagation and are generally nonlinear, tensor or complex quantities.

Absorption of electromagnetic energy occurs due to dielectric and magnetic losses, and losses on conductivity, which must be maximized to achieve maximal shielding efficiency. However, when electromagnetic waves fall on a material, there is a reflection from the boundary. The greater is the difference in the impedance of the media, the greater is the magnitude of the reflection coefficient.

When creating broadband absorbing coatings (BAC), the main problem is to harmonize the absorbing structure with the environment, i.e. to minimize the integrated effect of reflection.

There are several ways to reduce the reflection of monochromatic electromagnetic waves from conductive (reflective) surfaces.

The simplest way to reduce the reflection effect is a resonant type of radiation-absorbent material (RAM), which is based on the Salisbury screen principle. A layer (thin film) of absorbent (conductive) material is located at the distance $\lambda/4$ in front of the conductive surface. The incident energy of high-frequency radiation is reflected from the outer and inner surfaces of the RAM and an interference pattern of neutralization (suppression) of the incident wave is formed. Another design of the electromagnetic wave absorber is an absorber consisting of a layer of RAM with a matching quarter-wave layer of non-absorbing material in front of it. However, the absorber operates effectively only at a fixed frequency and with a normal incidence of the wave on the conductive surface, so this method is of little practical use.

Another way to reduce the reflection is based on the fact that the wave resistance of a non-conductive material is determined by the ratio $Z = \sqrt{\mu_a/\varepsilon_a}$, where μ_a and $\varepsilon_a -$ are the absolute magnetic and dielectric permeability of the non-conductive material respectively. A impedance Z equal to the resistance of free space can be obtained by choosing the required ratio of these parameters.

If hysteresis loops for μ_a and ε_a are the same, i.e. such that for any pair of electric and magnetic field strengths the ratio μ_a/ε_a is the same, then the layer of such absorbing material for the incident wave in the case of a normal falling will be identical by its characteristics to free space.

Electromagnetic wave absorbers can be divided into the following types according to their operation principle [3]:

- interferencial, they apply the principle of mutual quenching the electromagnetic waves superimposed on the antiphase of incident and reflected waves;
- scattering, with the reduction of reflected energy in one direction related with scattering in other directions at different angles;
- absorbing, based on the conversion of electromagnetic wave energy into other types of energy (usually into thermal energy due to the presence of dielectric and magnetic losses of a material);
- combined, they combine different principles of operation in one absorber.

When developing single-layer broadband absorbers of electromagnetic radiation of the absorbing type, magnetodielectrics are usually utilized. For these magnetodielectrics a slight difference between characteristic resistances of the absorber of electromagnetic radiation and free space can be provided by selecting close values of relative dielectric and magnetic permeability. Moreover, an effective absorption can be provided due to large losses.

Futhermore, in [17] inhomogeneous absorbing materials were considered, in which the relative dielectric and magnetic permeability smoothly (for gradient materials) or stepwise (for multilayer structures) varied from values close to 1 on the outer surface to values that provided the desired level of absorbing an electromagnetic wave. This gradual change is achieved either by changing properties of the material, or by changing its geometric shape, that is performed in foam pyramids with carbon filling. Such absorbers usually have a relatively large bandwidth with a small value of the reflection coefficient and a small thickness of the absorber. But, it is difficult to implement them practically. An advantage of the gradient materials compared to the multilayer ones is no reflection at the boundary between the layers.

Single-layer materials with special frequency dependences of complex dielectric constant, multilayer and gradient materials are quite promising for development of dielectric absorbers with a wide operating frequency range.

Dielectric-based RAMs, such as carbon-filled plastics, have a relatively low density, while the coating thickness must be significant. To reduce the power of an incident wave by 20 dB and 30 dB, the coating thickness is determined by the following ratios:

$$D_{20\,dB} = \frac{0.279}{f \cdot \varepsilon}, \qquad D_{30\,dB} = \frac{1.65}{f \cdot \varepsilon},$$

where $f -$ is the frequency, $\varepsilon -$ is the dielectric constant.

Advantages of using ferrites with high magnetic permeability as thin-layer absorbers are a small layer thickness and a slight increase in the upper frequency of the operating range at a large layer thickness; the disadvantage is limitation of the operating range by low frequencies [17]. The advantage of ferrites with low magnetic permeability is that the lower limit of the operating frequency range is determined only by a position of the gyromagnetic resonance frequency, and the disadvantage is a large layer thickness required and a strong offset of the upper limit of the frequency range.

Developers pay great attention to RAM based on composite materials, in particular ferritresin mixtures with short metal fibers. Introduction of fibers in the amount of 1% to 3% of the mixture weight allows changing the dielectric constant in a wide range. To achieve unique features in the microwave range, materials with conductive inclusions of complex shape are used. They are: open and closed conductive rings, omega particles, single and bi-helixes, dielectric inclusions of various shapes with a high dielectric constant.

Also, RAM and structures based on resistive filaments located in a dielectric matrix are quite common [5]. The resistive filament is a multicomponent fiber with an electrically conductive composite inside it. The leading filler is carbon black with particles of size (30 …60) nm containing graphite crystals. The thread sheath has high strength, moisture-resistance and temperature characteristics.

Experimental studies of spectra of magnetic and dielectric permeability and absorption properties of composites performed in [13] showed that composite materials on carbonyl iron had high absorption properties in the frequency range (3 … 37) GHz at a small thickness of the layer. They can be utilized both as masking coatings on a metal surface and as protective non-reflective coatings with small values of reflection and transmission coefficients. The presence of a minimum reflection coefficient from a two-layer structure at frequencies above 37 GHz provides developing RAM for higher frequencies at an appropriate choice of the layer thickness.

In [10] nanostructured composite RAMs on a polymer basis were considered. They are capable to absorb electromagnetic radiation in a wide range of frequency and power and have a low cost. Moreover, to achieve maximal radiation-absorbing properties, they must meet the following conditions:

- the presence of a developed electrically conductive nanowire in the polymer matrix;
- the presence of nanoparticles of magnetic matter isolated from each other;
- providing additional attenuation of the electromagnetic radiation due to dielectric losses;
- the presence of structural elements that form Rayleigh structures and zones where waves are added in antiphase;
- realization of the minimal difference of wave resistances on the boundary between the nanostructured composite RAMs and air.

The study performed by the authors has shown that the above-mentioned conditions could be realized when introducing carbon nanotubes and nanofibers into the polymer matrix.

In [6] application of properties of nonlinear, amplifying, active and controlled complex media for the creation of thin broadband absorbers was considered. It was shown that the development of absorbers of this type was an alternative to commonly used materials with high values of magnetic and dielectric permeability as radiation absorbent coatings and that this would eliminate limitations of passive absorbers.

3. Modern technologies for improving the quality of components and construction of MRCs

Nowadays, the main part of the MRC hulls (in particular, pilotless aerial vehicles) is made of polymer composite materials (PCM). When developing MRCs, the world's leading manufacturers use the following state-of-the-art technologies:

- transgenic biopolymers are applied in development of ultralight, high-strength and elastic materials with high visibility characteristics for MRC cases [8];
- carbon nanotubes are used in electronic MRC systems and in composites to reduce electromagnetic radiation [14];
- microelectronic mechanical systems that combine microelectronic and micromechanical elements [20];
- hydrogen engines, which can significantly reduce the level of noise [4];
- intellegent materials that change their shape or perform some given function under external actions [2];
- intelligent composites or specially structured systems consisting of subsystems for reading a signal (action), its processing, response generation, and of mechanisms of feedback, self-diagnosis and self-recovery;
- self-healing materials: polymers, ceramics, metals and graphene-based materials [1];
- magnetic nanoparticles, which are a hop in development of storage devices; they expand significantly computing capabilities of robotic and umanned systems; the potential of the technology, which is achieved by using nanoparticles with a size of 10 to 20 nm is 400 Gbps/cm^2.

In the USA, a fiber with a thin-film coating in which solar cells are integrated is being developed. Such fiber is planned to be used for the manufacture of structural fabric capable to generate electricity for MRCs and for its payload. If this project completes successfully, developers will receive a new design material that will create light small MRCs with a long autonomy time [11].

Strategic directions for the MRC creation should be:

- development of materials for the case and engine;
- improvement of visibility reduction technologies;
- development of polymer composite materials on carbon and glass fillers having a unique set of properties: high elastic-strength characteristics (strength up to 2.5 GPa, modulus of elasticity up to 160 GPa), low cost production, high radiation transparency, low moisture absorption and high resistance to shock loads (strength of carbon fiber in compression after impact in more than 200 MPa).

It should be mentioned that the development and production of a modern MRC is not the problem of machine, ship or aircraft construction in their traditional sense. A distinctive feature of MRC is its focus on the task to perform. In this case, the device performs an important, but one of many functions – transportation, and the key word hear is "complex".

For the production of MRs of a new generation, it is necessary to take the following actions for improving the quality of components and design:

- development and production of modern construction materials: composite, with nanocoatings, welded, corrosion-resistant aluminum-lithium alloys of low density, welding technologies in solid phase [9];
- physical integration of the onboard equipment and various systems in the MRC;
- improvement of modern computer technologies, including multiprocessor systems for data collection, processing and storage;
- development of automatic control systems connected to information transmission, encryption and data compression systems;
- development of technologies of highly stable and noise-immune means of communication;
- improvement of remote technologies for probing the environment (radar, optoelectronic systems, multifunctional sensors);
- development and application of energy technologies, use of alternative energy sources: ultra-large capacity batteries, solar energy, large-capacity fuel cells;
- application of GNSS satellite navigation tools and systems and geographic information systems to provide accurate positioning of MRCs;
- improving the technology of image processing and pattern recognition;
- improvement of human-machine interface technology and artificial intelligence systems;
- development of technology of high-speed control systems to provide stability and controllability of MRCs in order to eliminate different negative effects and stochastic loads during the movement;
- creation of a power plant with a high efficiency to provide energy capacity and specific power as well as maximum duration and secrecy of movement, which requires the use of new materials and technologies;
- development of an improved visibility reduction technology, that is implementation of a special MRC design and application of radiation-absorbent, radiation-scattering and adaptive materials and coatings in the MRC design.

4. Methods of detecting low-observable objects

As can be seen from [19], application of architectural protection of the mobile object and radiation-absorbent material provides reduction of the effective reflective surface of an object by 10 times or more. Whereas intensity of the received radar signal is a function of the distance to the object in the fourth degree [15], it reduces the detection range by 1.5 ÷ 2 times.

Thus, the low-observable objects have the following features:

- the level of a reflected radar signal in the direction of a receiving antenna is reduced significantly due to radiation absorption and reflection in other directions, resulting in a decrease in signal-to-noise ratio;
- reflection of the radar signal from flat surfaces of relatively large size occurs with formation of a narrow pattern and the presence of side petals;
- reduction of a distance to the radio horizon by choosing appropriate architectural forms of the low-observable object.

From the above mentioned, we can identify the following areas for developing methods of detecting low-observable objects in radiolocation:

- development of methods for detecting objects by a direct reflected radar signal coming to a receiving antenna of the radar;
- increasing the distance to the radio horizont for stable detection of objects;
- establishment of a radar surveillance system so that the radar signal reflected from the object can be used for detection.

According to the first direction, it is necessary to determine the power P_D of the received reflected signal from the radar range equation considering parameters of the radar for a common antenna for transmission and reception:

$$P_D = \frac{P_B G_A S_A \sigma}{16\pi^2 D^4} = \frac{P_B S_A^2 \sigma}{4\pi D^4 \lambda^2}, \quad (1)$$

where $\frac{P_B G_A}{4\pi D^2}$ – is the radiation power of the probing pulse at the distance D from the radar with the radiant power of the radar P_B; $G_A = \frac{4\pi S_A}{\lambda^2}$ – is the antenna gain factor; $\sigma -$ is the effective scattering area for the inconspicuous object; $S_A -$ is the effective area of antenna aperture; $\lambda -$ is the wavelength at which the probe pulse is radiated.

Thus, reducing the effective scattering area of an low-observable object results in a proportional reduction in the power of the received reflected signal. The influence of this factor can be reduced technically by increasing the power of the probe pulse of the transmitter, increasing the sensitivity of the receiver, as well as choosing the optimal antenna design.

Since reducing the effective scattering area of an inconspicuous object decreases the signal-to-noise ratio of a receiver, the effectiveness of detecting low-observable objects depends on methods and algorithms used to process radar information.

Consider methods to improve the efficiency of detection based on hardware. An obvious method is increasing the energy of the probing signal of the radar by increasing the pulse power and its radiation time. But, it is difficult to implement. There are currently no appropriate technical facilities to increase tenfold the energy of the probing signal of the radar by increasing the pulse power, while increasing the duration of the probing pulse τ_{PP} will lead to a deterioration in the radar resolution at a distance $\Delta D = 0.5 c \tau_{PP}$, where *c* is the speed of light.

The real way to increase the energy is to radiate not one but several pulses, which differ in code, during the probing period. This allows to get rid of ambiguity when determining the range of the received signal for a number of pulses in the packet without slowing down the survey. This method was implemented in [19], where a coherently built pulse radar using signals with intra-pulse phase manipulation was proposed.

The energy of a received signal can also be increased by increasing the number of reflected signals in the packet, that is the accumulation time of reflected signals. However, implementation of such an approach may lead to a slowdown in the controlled area survey and, consequently, requires more radars. To eliminate this shortcoming, in [21] a modification of this approach is proposed, at which there is an increase in the signal-to-noise ratio with almost no increase in the reflected signal energy. Also, the method performs compression of primary radar information without information loss, which is especially important because the processing of radar information must be performed in real time.

As can be seen from the basic radar equation (1), the power of the received reflected signal P_D is proportional to the square of the effective area of the antenna aperture S_A and depends linearly on the effective scattering area of the inconspicuous object. Therefore, the effect of reducing the effective scattering area of an inconspicuous object can be significantly offset by developing or selecting an appropriate antenna design. It should be noted that only a systematic approach to the selection of antenna design will be effective. This approach considers the increase in the energy of reflected pulses due to increase in the signal-to-noise ratio caused by the antenna pattern opening.

Therefore, we can conclude that only with a systematic approach to selection and development of technical facilities, and with appropriate methods and algorithms for processing radar signals operating at low signal-to-noise ratios the effects of stealth technologies based on reducing the reflected signal level can be significantly neutralized and the probability of detecting an low-observable object can be increased.

The distance to the radio horizont depends only on the height of the antenna and the height of the object. Therefore, when reducing the height of the object, it is necessary to increase the lift of the radar station antenna, which depends on the tasks performed by the station [16]:

$$D_{LS} \cong 4.12\left(\sqrt{h_A} + \sqrt{h_T}\right), \quad (2)$$

where $D_{LS} -$ is the line of sight, km; $h_A -$ is the height the electric center of the antenna, m; $h_T -$ is the height of a target, m.

Thus, reducing the height of the target from 3 m to 1.5 m with the constant height of the electrical center of the antenna reduces the range of direct visibility by 2 km. On the other hand, for continuous monitoring the area of a width up to 200 km at a minimum target height of 1 m, it is necessary to raise the antenna to a height of at least 2300 m, which is possible only when placing the antenna or radar on an aircraft. Application of air-based radars depends on solving problems of dynamically complex operating conditions and on methods and algorithms for detecting objects against the background of signals reflected from the earth's or water's surface.

It should be mentioned that irradiating the object at an angle to the horizontal plane changes the effective scattering area, which can increase the efficiency of low-observable object detection. In addition, it is possible to detect objects by their interaction with the aquatic environment (waves that diverge behind the object, turbulence of surface layers of water, excitation of wave processes in water, changes in physicochemical properties of water, etc.). However, at present, these processes are insufficiently studied in terms of radar visibility, which does not allow them to be fully used in the inconspicuous object detection.

Multi-position radars in the mode of cooperative work are used to detect objects of stealth technology by a probe signal reflected in another direction. A special case of the multi-position radar is a two-position (spaced) active location system with one transmitter (bistatic system). The cooperative reception of the reflected signals implies the use of the secondary radiation of the object, which is probed from any one position, at different positions.

5. Conclusions

The state-of-the-art technologies used by the world's leading manufacturers in the development of low-visibility MRCs have been outlined, as well as perspective measures aimed at improving the quality of components and structures of such facilities.

Methods of detecting objects using stealth technologies have been considered, and it has been shown that only due to the system approach it was possible to compensate for reduction of the effective scattering surface of low-observable objects by radar technical facilities.

Since the invisibility of the object results in a decrease in the signal-to-noise ratio, this parameter must be maximized in the radar receiver.

It has been shown that the main method of increasing the range to the radio horizont is the application of air-based radar. To organize a common operation of several radars at detection of low-observable objects, methods of detecting objects by traces of their interaction with environment (in particular, water) are quite perspective.

The problem of the detecting objects of stealth technology can be solved only with a systematic approach to implementation of all considered radar technical facilities and with a development of methods and algorithms for detecting objects that operate at low signal-to-noise ratio.

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SMART POWER WHEELCHAIR: PROBLEMS AND CHALLENGES OF PRODUCT APPROACH

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Abstract. *This paper focuses on intelligent assistant for power wheelchair (PW) usage in home conditions. Especially in the context of PW intelligent assistant as a consumer product. The main problematic aspects and challenges of smart PW in real application are noted. The approach to formation of system requirements and their classification is offered. The research results proposed and implemented in the ongoing Mobilis project for smart PW. Further prospects of research and development are noted. Also, it is stated that the implementation of smart PW technology opens possibilities to effective integration with new control methods (including brain-computer interfaces).*

Keywords: power wheelchair, intelligent systems, drive assist systems, autopilot, human-computer interaction

INTELIGENTNY WÓZEK INWALIDZKI Z NAPĘDEM ELEKTRYCZNYM: PROBLEMY I WYZWANIA W PODEJŚCIU PRODUKTOWYM

Streszczenie. *Niniejszy artykuł koncentruje się na omówieniu problemów i wyzwań dotyczących nowego produktu, jakim jest Smart Power Wheelchair (SPW), czyli inteligentny asystent używany w elektrycznych wózkach inwalidzkich w warunkach domowych. Zwrócono szczególnie uwagę na ukazanie SPW jako nowego produktu konsumenckiego na rynku dóbr. Przedstawione zostały główne problematyczne aspekty i wyzwania dla SPW, które mogą pojawić się w warunkach rzeczywistych. Artykuł zawiera również propozycje dotyczące tworzenia wymagań systemowych oraz ich klasyfikacji. W kolejnej części artykułu przedstawiono wyniki badań, zrealizowanych w ramach projektu Mobilis, dzięki którym wdrożono szereg zmian w produkcie. Ponadto autorzy zapewniają o planowanych dalszych badaniach nad rozwojem produktu. Należy zwrócić uwagę, że wprowadzenie technologii SPW otwiera możliwości efektywnej integracji z nowymi metodami komunikacji (w tym z interfejsami mózg-komputer, z ang. brain-computer interfaces – BCI), z których szczególną korzyść będą miały osoby z niepełnosprawnością ruchową.*

Słowa kluczowe: elektryczny wózek inwalidzki, inteligentne systemy, systemy wspomagania napędu, autopilot, interakcja człowiek-komputer

Introduction

Low birthrate and long span of life tend to rapidly advance, especially in the economically developed countries [12, 23]. In such society the demand for the specialized care and mobility products for the disabled persons, based on new technologies, is increasing, not only to support their physical abilities but also to decrease the care complexity. Power wheelchairs (PW), as classic assistive devices, are widely used by elderly persons and disabled people as they require minimal physical efforts for motion [12].

According to the statistics of the World Health Organization (WHO) 15% of the world population suffer from a disability and from 2% to 4% experience considerable problems in practice. Global assessments of the disability increase with the ageing of the world population and improvement of the assessment process and disability measurement [9, 14].

Mobility is one of the key components of supporting high quality of life. Elderly people and people with disabilities which hinder walking or using manual wheelchairs are often offered power wheelchairs (PW) to help them move independently in their environment. Decision making, regarding the application of PW is based on certain factors, including the safety of the driver and other persons in the environment, forecast benefits for the driver, possibility of PW access and available funding [4, 21].

Assessment of the possibility of the application and PW selection comprises complex monitoring of the numerous factors, influencing the readiness of a separate person to use PW and the selection of the corresponding PW, taking into account the needs and available situation. In the process of decision making and PW selection it is necessary to perform the efficient training of PW driving to make the future user a safe, efficient and polite driver [4, 21, 22].

1. Classic power wheelchair driving challenges

for a great number of people, who require long-term care. The examples of the diagnosis which may influence the ability of the person to control safely PW are dementia, cerebral palsy with cognitive disorders, amyotrophic lateral sclerosis, severe traumatic Brain Injury, multiple sclerosis and Parkinson disease, syringomyelia, myasthenia, consequences of cerebral and spinal strokes [4, 10, 17, 21].

In general the PW driving process may be schematically shown as a cyclic sequence of tasks:

$$\text{Perception} \rightarrow \text{Planning} \rightarrow \text{Steering}.$$

To provide mobility for more people, the solution has to overcome limitations on each step of the sequence.

1.1. Perception limitation

Head movement may be limited due impairments, so users cannot look around to observe all surrounding space. The same applies to visually impaired people.

The importance of this position is justified by the fact that a significant proportion of PW users (especially elderly people) may have problems with vision, hearing, vestibular analyzer which significantly complicates their orientation in space. In particular, coordination disorders due to pathology of the brain and pathology of the vestibular analyzer; diplopia, a significant decrease in visual acuity; neurosensory deafness, etc. This may in various combinations be a manifestation of the above pathology or a consequence of comorbidity [20].

1.2. Planning limitation

Some people with cognitive deficits cannot operate wheelchair, as they may have difficulties with prediction and/or planning wheelchair motion.

Safe operation of PW requires a sufficient level of the cognitive functions, ability, including decision making, memory, judgements, self-consciousness. Certain studies show that 60–80% of the patients of Long-Term Care (LTC) have dementia. Diminished attention, poor operation control, loss of memory problems are the known features, connected with different forms of dementia, including Alzheimer disease, which make independent navigation of PW difficult or impossible. Determining the acceptability of PW using, the doctors face the difficult decision, connected with the needs of their patients in the independent mobility, safety of the driver and others in the environment [22].

1.3. Steering limitation

For user with severe motor impairments (like amyotrophic lateral sclerosis or spinal cord injury, cerebral palsy, etc), traditional control interfaces, such as a 2-axis joystick, are not suitable, as they require precise movement control over the limbs, which in their case is not possible.

Usage of a joystick requires prior training for obtaining sufficient operation skills, especially in case of motion in narrow places or in crowded places, in places with high concentration of different objects. That is why, emergency situation caused by the operation errors occur among elderly people not only as a result of sensitivity decrease due to ageing but also as a result of the difficult control of the system according to the report, issued by the Tokyo Metropolitan Police Agency (Japan), 200 cases of dents are connected wild the automobiles and power wheelchairs, happen each year. 25% of these cases belong to the operating errors [12].

2. Smart power wheelchair as a solution

Taking into account the above-mentioned problems of driving PW the development and implementation of Smart Power Wheelchair (SPW) is required, as a solution. SPW should be able to avoid collisions and support navigation, simplifying control tasks for the user.

Existing scientific research also stated that for the safe motion of PW it is better to use the autopilot-like smart drive assist system, overcoming the limitation of the control during the usage of the joystick, voice commands, etc. [12].

The development of SPW is an important scientific-applied problem, involving large groups of population and has significant social value.

The analysis of the literature sources related to SPW, reveal significant activity during the last 20 years. Many SPW research projects resulted in identification of certain problems, connected with the convenience of usage and spheres for improvement [5, 8, 7, 11, 12, 14, 15, 16, 21, 22].

Highly appreciating the tremendous efforts, made by the numerous researchers in the field of the development of the smart PW, authors state that the development of the intelligent assistant of PW, in particular in the sphere of SPW usage in home conditions is still open problem, especially in the context of making SPW consumer mass product.

3. Requirement for smart power wheelchair

According to study [19], PW users most of the time (64%) drive indoors (mostly at home). Authors believe that home drive is a most important use case for SPW technology and effective operation of SPW in home conditions is a key to a successful mass product. Thus, specific requirements for home driving need additional research.

However, driving in such a crowded environment as a user's home implies a set of specific requirements that significantly differ from driving in other conditions (e.g. hospitals, airports, research labs etc.). Moreover, home driving in many aspects is more complex than driving in large spaces, so successful implementation of smart home drive assistance system will be helpful to implement other use cases.

When SPW is used in home, these conditions are characterized by the increase system requirements to the accuracy of the driving (decrease of the distance to the obstacle while moving – along the wall, passage across the narrow doorways, etc.), need of the dynamic monitoring of the environment and reconstruction/updating of the 3-D map of the premises (in the process of the object position change, motion of the domestic animals, change of the usual position of the objects after cleaning by the outsiders) peculiarities of the decision making regarding the possibility of the passage with minimal possibility of injuring the person-user due to inaccuracy/error of the intelligent system (passage with the hanging/suspended obstacle, that can injure person-user; rapid acceleration of SPW and injuring while emergency braking, problems with the correct parking of SPW if there is a need to pass to bed or from the bed, etc.), and problem of the absence of the person-assistant for rapid help in the emergency situation (impossibility of letting such person in), etc.

Table 1. Reasonable hi-level user's expectations from SPW

Driving sequence step	Reasonable expectation from SPW
Perception	Perception required to drive is lowered by 10X. For example, ~10% of eyesight field should be sufficient to operate SPW.
Planning	Planning requirements is lowered from drive path to end goal.
Steering	Steering precision requirements is lowered by 10X. User just provides direction or intent with control interface and system does actual steering. The system should operate with rough direction command and be able to compensate tremor.

Also, modern methods of control should be taken into consideration in the research and development of SPW, in particular Brain Computer Interface (BCI). The combination of SPW technology with BCI basically opens new prospects and functional possibilities. Accuracy and reaction speed of BCI systems are rather low. On the other hand, intelligent assistants for PW decrease the requirements to the perception, planning and steering for PW. Thus, there appears the possibility of efficient integration – the user shows his intentions by means of the BCI system and real motion control is performed by the control system of SPW [2].

Hence, in the given study the authors focus attention on home use of SPW. Based on some individual research conducted using actual PW driving experience of several people, and interviews with many PW users, a list of requirements that seems reasonable, have been created and refined in view of modern publications [1]. The system requirements for mass market SPW categorized, taking into account the factors, described above.

We believe that a mass product SPW should have following properties (in each section, requirements listed in order from most important to less important).

Steering precision requirements

"The Smart Wheelchair Component System" (AKA SWCS) [18], proposed a list of criteria for an effective wheelchair drive assist system. While the criteria seem reasonable and well developed, we believe that the actual system for indoor use should provide much more precise operation, to be practical for home usage.

Table 2. Main requirements

Key metrics	Required value
Minimum average obstacle clearance in "safe" mode	5 cm
Minimum diameter of an obstacle that can be detected	2.5 cm
Maximum distance from an object (e.g., table) when docking	5 cm
Maximum distance from wall when following a wall down a hallway	5 cm
Minimum door width the system is capable of passing through	70 cm

Mechanical requirements

- System should not change overall size of wheelchair (as this critically important to keep physical maneuverability of the platform);
- System should not make onboarding and offboarding to the wheelchair more complex;
- System should control wheelchair with centimeter-grade precision (to support operation in crowded spaces);
- System should discover mechanical parameters of the wheelchair automatically (probably, by selflearning algorithms);
- System should not require high mechanical precision during installation: height, angle, vertical and horizontal align should have big tolerances ~20% (probably, system should use self-calibration after mount);

- System should adapt to change of parameters of wheelchair during lifetime wear (probably with calibration / tuning during operation).

User interface requirements
- System should support regular joystick (or other existing controller) operations (smart functions should assist driving, while direction controlled in familiar way);
- System should allow operation with serious mechanical control noise because of user's condition (like tremor, imprecise finger movements, etc.);
- System should support touch screen interface with wired touch screen attached to wheelchair and/or wired/wireless connection with user's smartphone/smartwatch;
- Ability to lock certain parameters or functions to prevent user to accidently modify them (to allow operation for children and/or patients with affected cognitive abilities);
- System should support voice commands;
- System should provide voice feedback in case it seriously alters user maneuver (so user will be aware of reason of wheelchair evolution);
- System should support integration with other control methods (pneumatic sensors, lip movement stick, head tilt, etc.).

Basic functional requirements
- Collision mitigation (safe stop in front of obstacle);
- Collision avoidance (system should try to drive around obstacle, in case free pathway exist);
- Walls follow (drive near the wall keeping reasonable safe distance);
- Ramp driving assist (drive in center of accessibility ramp);
- Door passage assist (driving keeping in center of doorway, taking into account that typical doorway may be 70 … 75 cm wide);
- Limit application of emergency braking (try to gracefully slow down when possible);
- Stairs detection (upstairs and downstairs);
- Unexpected obstacle mitigation / avoidance (if something appears in front of wheelchair it should apply brakes with delay no more than 200 ms);
- Sidewalk drive assist (keep direct movement on sidewalk in case its visual borders are clearly visible).

Advanced functional requirements
- Automatic (or semi-automatic) construction of 3D map of user's apartment for future autopilot navigation with space no less than 100 m^2;
- Provide ability to set predefined destination and desired orientation of wheelchair on constructed 3D map;
- System should be able to find its location (automatically or semi-automatically) on existing map after been switched off and moved to new location on known apartment or detect that location is unknown (say, wheelchair transported to new building);
- Provide ability to drive to predefined destination automatically in known environment (with digital map exists) as "hand-off" autopilot (with minimum requirement to apartment);
- Provide ability to automatic map refresh in case of small interior changes (furniture movement, new random small objects on floor);
- Provide ability to drive to predefined destinations automatically in a known environment (with digital map exists) as "eyes-off" autopilot (probably with some additional requirements to apartment).

Electronic requirements
- System should be compatible with wheelchair power system (at least with popular 12V and 24V versions);
- System should consume <20W of electric power to (keep wheelchair range not affected);
- System should be able to enter power-saving state (< 5W, wakeup time < 200 ms) when not in use (when wheelchair is not moving > 1 minute [configurable]);
- System should be able to enter sleep state (< 1 W, wakeup time < 1 s) when not in use (when the wheelchair is not moving for > 20 min [configurable]).

Sensor requirements
- System should not rely on GPS (or alike) satellite navigation systems (as using these system indoors may not provide enough precision);
- Sensors should be located in places, where they have fewer chances to be affected during regular operations (far from legs, lower regions that be subject of impacts, dirt, mud etc.);
- Sensor should provide precisions about 1cm on area about 2m×2m in front of wheelchair;
- Sensor system should be extendable to support rear sensor for driving backwards;
- System should not require apartment interior changes (like putting visual markers or RFID beacons) in most real word operation scenarios.
- System should be able to work without relaying to any radio technology ("no antenna") for operation. For example, a system should not be dependent on GPS (as it may not work well indoors) or RFID (as it requires markers pre-placement procedure).

Safety requirements
- System should have a self-diagnostic system to inform users about malfunction and stop operation or reduce wheelchair speed to safety margin like 0.1 m/s [configurable].
- System may implement concept of optional "RED ZONES" (zones where wheelchair driving is not safe for some reasons), so system will not allow drive to these places (zones may be marked ether digitally on map or visually with, say, red strips on floor);
- System may implement concept of optional "YELLOW ZONES" (zones where wheelchair driving speed should be limited for some reasons), so system will not allow overspeed drive in these places (zones may be marked ether digitally on map or visually with, say, strips/pattern on floor). Also these zones may be marked as zones restricted for full-auto drive (so wheelchair will drive there only with explicit user command);
- System may implement concept of "GREEN ZONES" (zones, where a stationary object may be detected as an obstacle, but the obstacle is passable by wheelchair). For example, the wheelchair technically may be capable of overcoming obstacles with height of 10 cm (for example, door threshold), if driven with caution. By default, wheelchair will threat anything with height > 2.5 cm (configurable) as an obstacle;
- System should be configured to apply emergency stop in case the user provides an explicit stop command or removes hand from the joystick (or other controller).

Optional requirements

While these requirements not required to core system operation, it may provide additional benefits:
- System may be able to be installed on existing wheelchair (at least on several popular models);
- System may provide functionality of uploading constructed 3D indoor map (with or without market navigation points) to the external storage (or cloud), so other wheelchair may be used in same environment (via wired or wireless interface);
- System may provide functionality to download ready constructed 3D indoor map (with or without marked navigation points) from the external storage (or cloud), so may easy adapt to new space, like entering new building (via wired or wireless interface);
- System should not require usage of odometers, but may use them in case they are available (as installation of odometers virtually impossible on existing wheelchairs);
- System may use MEMS accelerometers and gyroscopes to better movement tracking (as they are cheap and can be installed easy on existing wheelchair);
- System may support operation on multi floor building;

- System may support extended space operations by using external memory and additional external means.
- System may be integrated with external systems (patient state monitor, hospital information system, prescribed movement schedule inside hospital, elevators, tracking report systems etc.).

4. Smart power wheelchair implementation challenges

Similar to the requirements, authors define the basic problems and challenges in key areas.

Functional challenges
- The user's apartment layout is constantly changing. Furniture may be shifted, floor patterns may be changed (for example, by different carpet installed), so a constant 3D map or pre-recorded path becomes obsolete within the timespan of hours/days.
- Moving obstacles may prevent usage of stable (or pre-calculated) route.
- Driving around obstacles may require route replanning. To drive around, the wheelchair should seamlessly switch from "low-level" follow path mode to "hi-level" navigation tasks.
- User comfort depends on human tolerance to accelerations. Acceleration value and direction should be considered.

User Interface challenges
- Low Precision. Reasonable goal is to 10X reduction of precision required (user just shows direction).
- Noisy physical input. Tremor compensation vs fast response (smart low pass filtration + additional level of DNN to extract intent).
- Voice control drive. Operate a wheelchair with simple commands like “forward”, “backward”, “left”, “right”, “stop”, “slower”, “faster”, etc.
- Auto drive destination marking (autopilot should be able to provide an easy way to specify destinations).

Mechanical challenges
- ~5 cm clearance required to pass through narrow doors (for example, to pass 60 cm wheelchair in 70 cm doorway).
- Wheelchair rollers may have mechanical hysteresis (their position depends on previous turn direction).
- Occupant pose may affect actual motion platform shape (the occupant pose may be non-constant).
- Mechanical properties are not constant (slowly change due to physical wear or battery condition).

Electronics/Software challenges
- Wheelchair has a complex shape at ~5 cm detail level.
- Route planning algorithms should take into account actual wheelchair shape, as in tight environment approximation of wheelchair with simple shape may not work.
- To drive a wheelchair around collision several strategies may compete, as there are many maneures exist that may drive around.
- Result wheelchair orientation may be important for future driving.

Safety challenges
- Reliability of automatic driving software. For example, the system should apply "safety stop" and brakes in case it detects an operation anomaly.
- Predictable (Custom) Limitations. It should be possible to define "restrictions" on the map, so a wheelchair will not drive to said zones automatically.
- Emergency stop. User should have a clear ability to issue emergency stop command.

5. Mobilis project approach for smart power wheelchair

The goal of Mobilis project is to create an autopilot for power wheelchair: Smart AI module that transforms a regular power wheelchair into a smart personal mobility platform. The system will use 3D cameras and regular video cameras to do all the motion tracking and collision avoidance. For automatic driving, 3D map of the user's apartment will be constructed automatically [1].

The goal is to provide several levels of automation: from simple collision avoidance and semi-automatic driving to fully automatic driving indoors. The solution will integrate the wheelchair and user's smartphone (smartwatch) as well.

Mobilis project plans to use 3D cameras with the option to use cameras of several types (stereoscopic cameras, laser pattern projection technology, TOF cameras) for different product versions. Also, regular video cameras will be used as additional visual sensor input (including visual motion tracking and 3D map construction in natural colors).

The primary sensor (stick approximately 10 cm × 1cm size) is planned to be located under the joystick (3D and regular video camera). The sensor is located under the joystick facing 20-60 degrees downward. This allows seeing both the surrounding space and bottom of the wheelchair simultaneously (in both 3D and video). Additional sensors may be located on opposite arm-rest and at the back of the wheelchair (to allow drive in rear direction).

Accelerometers and gyroscopes (as MEMS chips) will be (optionally) used as additional sources of motion data. Odometers are not required for operation, as visual motion tracking will be the primary source of motion data (odometers may be used if available). Because odometers are not required, this radically simplifies installation on existing wheelchairs as it is not required to alter mechanical powertrain.

To achieve goals of precise and stable collision avoidance and route planning an alternative approach (compared to conventional VFF and VFH algorithms) will be used: new Multipath route planning algorithm. Algorithm is performing path prognosis by modeling wheelchair movements in accelerated time. In practice, the wheelchair constantly performs a series of computational experiments to evaluate optimal path.

For autopilot operation, a special 2-level strategy route planning algorithm will be used (selection of intermediate goals, while goal-to-goal transfer will be done by Multipath algorithm).

To implement solution that can be used in mass production and deployment on different wheelchairs, several important issues should be taken into consideration.

Initially the wheelchair parameters are known only approximately. Moreover, even if the wheelchair model is known, a particular wheelchair may have seriously different actual parameters due to manufacturing process instability, wear, battery condition, occupant weight etc. That is, PW itself is not a precise electromechanical system.

Installation of system components may be performed with serious deviations (±20% tolerance). The system should be able to self-calibrate during installation (and fine-tuning during operation).

Many solutions imply long calibration stages to adapt to a particular wheelchair. Mobilis approach is to discover actual parameters by self-learning method.

To fine tune parameters neural network will be used to select appropriate model parameters. To avoid computational instability in case a model tuned by a neural network will operate out of a known dataset, a rough simplified model will be used as source of “reasonable corridor” of calculated evolutions.

Integration with existing wheelchairs planned to be implemented via Mobilis Connector component that acts as a proxy between joystick and motor power controller, providing full “drive by wire” possibility. As a safety fallback mechanism, “pass through” mode may be activated, so the joystick will drive the motor controller directly, without smart module functionality.

6. Discussion and conclusions

Research on the Mobilis project is developing a platform that combines PW with a user's smartphone and a wireless control system to implement Smart Power Wheelchair. The platform connects intelligent software and hardware modules. Mobilis solution is designed to equip most existing (or new) PW with 2-engine layouts with various sets of additional features, including: smartphone control, automatic obstacle avoidance and home autopilot [1, 3, 13].

During Mobilis Power Wheelchair Autopilot project, test drives and interviews with people with disabilities were conducted that allowed to summarize and prioritize consumer expectations and system requirements. Also, considerable work has been done to identify problems and challenges faced by SPW operating at home conditions.

Future research of certain tasks requires a comprehensive combination of methods of artificial intelligence, 3D computer vision, machine learning, mathematical modelling, ergonomics and robotics.

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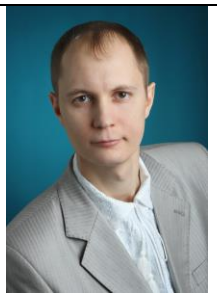

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IMPROVING THE ACCURACY OF VIBRATION MEASUREMENT RESULTS

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Abstract. *The current state of control of vibration measuring equipment is studied in the work, the analysis of technologies of control of vibrating measuring machine equipment is carried out. It is determined that during the control a sufficient requirement for the analysis of changes in the state over time is to conduct periodic vibration measurements in the same modes of operation of the object. Therefore, the urgent task is to increase the reliability and accuracy of measurement results. It can be enhanced by obtaining additional information. For this purpose, recommendations for optimizing the vibration control points of the mechanism are formed. To increase the accuracy of measurement results when controlling the equipment for vibration signals, the methods of mounting the measuring transducer in the equipment monitoring system are considered. It is shown that the method of mounting the measuring transducer can affect the results of vibration measurements.*

Keywords: vibrations, measuring transducer, vibroacoustic parameters, vibration measurement

POPRAWA DOKŁADNOŚCI WYNIKÓW POMIARÓW DRGAŃ

Streszczenie. *W pracy badany jest aktualny stan sterowania wibracyjnymi urządzeniami pomiarowymi, prowadzona jest analiza technologii sterowania wibracyjnymi urządzeniami pomiarowymi. Stwierdzono, że podczas kontroli wystarczającym wymogiem do analizy zmian stanu w czasie jest prowadzenie okresowych pomiarów drgań w tych samych trybach pracy obiektu. Dlatego pilnym zadaniem jest zwiększenie wiarygodności i dokładności wyników pomiarów. Można go ulepszyć poprzez uzyskanie dodatkowych informacji. W tym celu formułowane są zalecenia dotyczące optymalizacji punktów kontroli drgań mechanizmu. Aby zwiększyć dokładność wyników pomiarów przy sterowaniu aparaturą na sygnały wibracyjne, rozważono sposoby montażu przetwornika pomiarowego w systemie monitorowania aparatury. Wykazano, że sposób mocowania przetwornika pomiarowego może wpływać na wyniki pomiarów drgań.*

Słowa kluczowe: drgania, przetwornik pomiarowy, parametry wibroakustyczne, pomiar drgań

Introduction

At the present stage of development in production, a continuous technological process is very important, which is ensured by trouble-free operation of the equipment. Thus, the study of oscillatory processes is of great interest to all sectors of the economy. For these purposes, work is being done to study the technical condition of the equipment and further analysis of its changes. Machine failures are accompanied by increased vibration.

The main task of monitoring the state with the help of the simplest system is the timely detection of the dangerous state of the mechanism, ie. minimization of the probability of omission of the developed defect, sufficient for the occurrence of an emergency situation between the periodic measurements of the controlled parameters.

Detection of changes in the state of the mechanisms using the simplest monitoring system can be done in the main way, i.e. by analyzing the changes in the controlled signals of the object and their parameters over time, as well as by comparing the values of these parameters in a group of identical objects at identical control points in identical operating modes. The second method allows you to assess the state of the mechanism by single measurements by comparing each of the controlled parameters with thresholds for each control point and each of the possible modes of operation. In this way, the thresholds are calculated from single measurements of these parameters in a group of identical mechanisms.

Carrying out a preliminary assessment of the type and magnitude of the possible fault allows you to identify the most dangerous defects to continue operation and decide on the decommissioning of the mechanism. In other cases, you can continue to operate the mechanism with reduced intervals between measurements to clarify the rate of further deterioration with a forecast of residual life or for professional diagnosis, which will significantly reduce the number of unreasonable conclusions of the mechanisms for repair.

This requires a constant increase in the requirements for the accuracy of measuring control points of equipment and methods of technical control, as part of technological processes.

Appropriate means of measuring, analyzing and transmitting information are an integral part of any information and measurement system for monitoring equipment based on any of the signal processing methods. Therefore, one of the urgent tasks is to increase the accuracy of measurement results during vibration control, which is considered a powerful tool for equipment diagnostics. Therefore, in order to obtain complete information and relate the accelerometer measurement data to the actual conditions and consequences, it is necessary to consider the methods of mounting the transducer.

1. Analysis of recent research and publications

Detection of faults that have not yet led to catastrophic consequences, determining the degree of development of the defect and its signs are possible only on the basis of a detailed study of the structure of vibration signals. Many studies have been devoted to the issue of vibration control of machinery [1–3, 5–13]. The work is devoted to research on the methods of signal analysis [1, 2, 7–9, 13], specializing in solving diagnostic problems, such as the method of shock pulses [2, 7] and the method of envelope [8, 9], which allow to solve a number of diagnostic tasks on one-time measurements of vibration or noise, and also methods of diagnosis on the basis of narrowband spectral analysis of signals [1, 13].

The work is devoted to numerous studies to study the effect of different types of defects [11, 12] on the operation of machines and diagnostic signals [6]. The results of these studies have shown that the greatest diagnostic information has a vibration signal, and many other types of signals almost duplicate one or another information contained in the vibration signal. In addition, it has become apparent that defects begin to develop long before emergencies occur. And almost immediately the defects begin to affect the vibrations and noise disturbed by these nodes. Therefore, the task of measuring and monitoring changes in the signals of the object and their parameters over time becomes relevant.

2. The purpose of the article

The aim of the article is to increase the accuracy of measurement results when controlling equipment for vibration signals, for this purpose we investigated the methods of mounting measuring transducers in the equipment monitoring system, which can affect the accuracy of vibration measurement results and the technical condition of equipment.

3. Presentation of the main material

Vibration control [4] of operating mechanisms is a measurement of the level of vibration in the standard frequency band at all control points of the mechanism, comparing the obtained values with the established ones and deciding on the compliance of vibration with the norms.

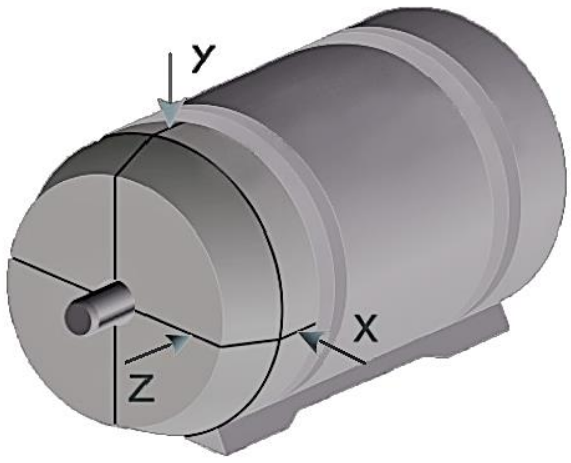
Therefore, increased vibration in machines can cause serious damage. Stresses caused by vibration contribute to the accumulation of damage in materials, cracks and damage. Such problems can be detected at the beginning using vibration measurement methods. Thus, there is a great necessity to measure, evaluate and control the vibration signals of industrial equipment.

The main requirement for the choice of vibration control points of nodes of controlled mechanisms is the identity of points, and for vibration and measurement directions of identical mechanisms, which allows to compare measurement results and build thresholds "by group" usually from ten identical control objects (their group thresholds for each point and control directions). For mechanisms that do not have "groups", thresholds are built "historically" after the accumulation of periodic measurement data for a time or about ten percent of the typical resource or, more commonly, at least a thousand hours of operation.

The main points of control of vibration of mechanisms by the simplest monitoring system are selected according to the current ISO standards in the direction of "Monitoring of a condition and diagnostics of cars", on the case of support of rotation. The main temperature control points for machine assemblies are also the fixed surfaces of the rotating assemblies.

Vibration at the main control points, in accordance with the recommendations of the current standards for vibration control of machines and mechanisms, should be measured in three mutually perpendicular directions, in particular, for horizontal mechanisms - vertical, horizontal and axial, as shown in figure 1.

Taking into account the direction of measurement, at least low-frequency vibration, often provides additional information to identify the condition of the mechanism. Vibration at medium and high frequencies to monitor the condition of mechanisms with a horizontal rotor is usually sufficient to measure in the vertical direction (in the direction of static load on the rotary bearings).



X – horizontal, Y – vertical, Z – axial

Fig. 1. Recommended directions of vibration measurement on support of rotation of mechanisms

In some cases, it is recommended to use additional vibration control points of the mechanisms for additional information. First of all, this is the point on the outer surface of the housing of the flow-converting mechanisms, where the flow rate is maximum. Measurements of high-frequency vibration at this point reveal problems with the formation of the flow of liquid (gas), and the comparison of the results of these measurements with the results of similar measurements on bearing assemblies – to separate the faults of bearings and impellers.

Another group of additional vibration control points is used to measure the vibration on the housing of some machines in the direction of rotation of the rotor (low-frequency tangential vibration) caused by pulsating torque components that act on the rotating parts and the housing. The points of control of such vibration must have a direction tangential to the body and be as far as possible from the axis of rotation and the points of attachment of the mechanism to the foundation. The most effective results are measured by tangential vibration in the case of elastic (on vibration isolators) fastening of the unit to the foundation.

All thresholds for the values of the measured vibration parameters that separate the sets of states of the controlled object are counted from the "base line" passing according to the statistical average obtained from the results of periodic measurements of the values of this parameter of a defect-free object, Fig. 2.

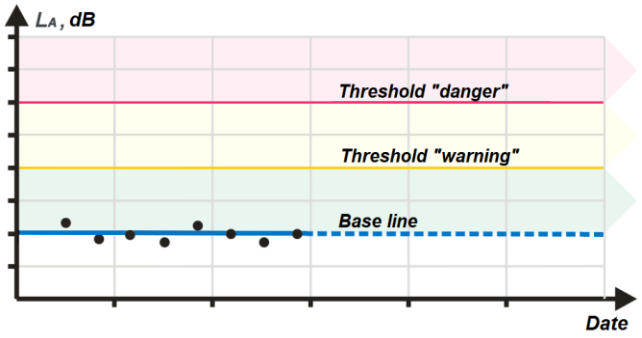


Fig. 2. Setting thresholds relative to baseline

When determining the "base line" values of the vibration level in the standard frequency band (general level), linear units are used (mm / s or microns for the general level of low-frequency vibration), for the components of the one-third octave spectrum of vibration acceleration - logarithmic units (dBA). The base line for RMS and Ultrasonic Vibration Peak can be plotted from measurements in both linear units (m / s^2 or g, in logarithmic scale) and in logarithmic units (dBA, in linear scale).

The base line for each parameter is determined by its periodic measurements in the nominal operating mode of the mechanism for a long time, during which several stops are performed for its periodic maintenance. In single-mode mechanisms, at least a high-quality control of the mode is necessary (control of the mechanism's output to a steady-state mode of operation). For multi-mode mechanisms, control should be quantitative (in terms of speed and, if necessary, in terms of load). A large statistical scatter of data when plotting the baseline of the controlled parameter indicates the ineffectiveness of the parameter used for monitoring the condition or the need for more accurate control of the operating mode of the mechanism.

The presence of a statistically significant slope at the base line (or on its statistically significant segment) indicates an ongoing change in state in the process of running-in (decline) or defect development (rise). In the first case, the base line needs to be refined after statistically significant stabilization of the measurement results; in the second, the residual resource can be predicted (until the “dangerous” threshold is reached, measured from the “base line” value determined at the beginning of the “base line” slope).

An analogue of the "base line" in the form of a statistical mean value of the monitored parameter (baseline value) can also be used to set thresholds for a significant (usually from ten) group of identical mechanisms. A feature of such a construction of the average value for the group is the possibility of getting into the used group of mechanisms with different operating time, including those with developing defects. In order to minimize the influence of such mechanisms on the results of assessing the average value for the group of defect-free mechanisms, it is recommended to carry out an additional assessment of the results obtained.

At present, the standard thresholds for vibration monitoring of the condition of mechanisms are determined only for the general level of low-frequency vibration. There are also generally accepted recommendations for setting state thresholds by the temperature of nodes or by vibration parameters, measured from the baseline (according to history) or from its analogue (according to a group of mechanisms). However, such recommendations can be used only for the initial period of operation of the simplest monitoring system. In the future, these thresholds should be specified for each type of mechanism.

In total, it is recommended to set up to 4 thresholds for the value of each vibration parameter:

- the lower threshold, determined by the lower boundary of the zone of permissible values of the controlled parameter of the operating mechanism,
- threshold "warning", which determines the upper limit of the zone of permissible values of the controlled parameter of the mechanism operating without restrictions,
- threshold "danger", which determines the upper zone of short-term admissible values of the parameter at the time of decision-making.
- "stop" threshold, exceeding which requires an urgent stop of the mechanism.

In many cases, for the most important of the monitored parameters, the last two thresholds are combined into one.

Typical recommendations for setting the thresholds "warning" (+ 10 dB) and "danger" (+ 20 dB) above the statistical average value can be used as thresholds for individual components of the one-third-octave vibration spectrum (when making decisions on a group of mechanisms).

When making decisions about the state of exceeding the values of the parameter over the baseline, one should take into account the significantly smaller scatter of the results of periodic measurements of the parameters of one mechanism in comparison with a group of mechanisms, especially in the low-frequency components of the vibration spectrum. Accordingly, the recommended thresholds for monitoring the state "by history" depend on the frequency of the spectrum component.

When determining the condition of the mechanism for the growth of RMS and the Peak of ultrasonic vibration, the thresholds for the RMS and the Peak are determined from the base line ("base line" when constructing thresholds for a group of mechanisms) for the RMS and are, respectively, 10 dB and 20 dB for the "warning" threshold, as well as 20 dB and 30 dB for the threshold is "dangerous". When controlling the geometric mean from RMS and Peak, the same thresholds are usually maintained as for RMS.

With the accumulation of data on false alarms (premature withdrawal of control objects for maintenance or repair), omission of dangerous situations and the results of independent defect detection of objects coming for repair (based on the results of condition monitoring), the thresholds in the monitoring system can be adjusted both in large and in the smaller side. After the accumulation of practical experience, it is possible to determine the thresholds for the urgent "shutdown" of mechanisms in the pre-emergency state. Until these thresholds are determined, it is recommended to use the "danger" threshold for the accelerated withdrawal of the mechanism for current repair.

When making decisions about the state of the temperature rise of the nodes of the mechanism, it is recommended to set any thresholds only after constructing a baseline and evaluating the RMS of the results obtained.

The simplest means of vibration control includes: a measuring transducer, an analyzer (actually a vibrometer), as well as an external program for collecting and analyzing measurements.

It is recommended to use an accelerometer with a natural resonance frequency of more than 25 kHz as a measuring transducer in the monitoring system. However, the method of attaching the accelerometer to the object can significantly affect the allowable frequency range of vibration measurements.

The best way to attach the accelerometer to the object is threaded, in which the resonant frequency of the accelerometer is practically not reduced (Fig. 3). However, this method involves the preparation of threaded holes for the stud at the control points of the mechanism, and when taking measurements requires additional time to twist / unscrew the sensor with the measuring cable. This is considered a disadvantage and therefore this method is not suitable for frequent use in periodic vibration measurements by portable monitoring systems.

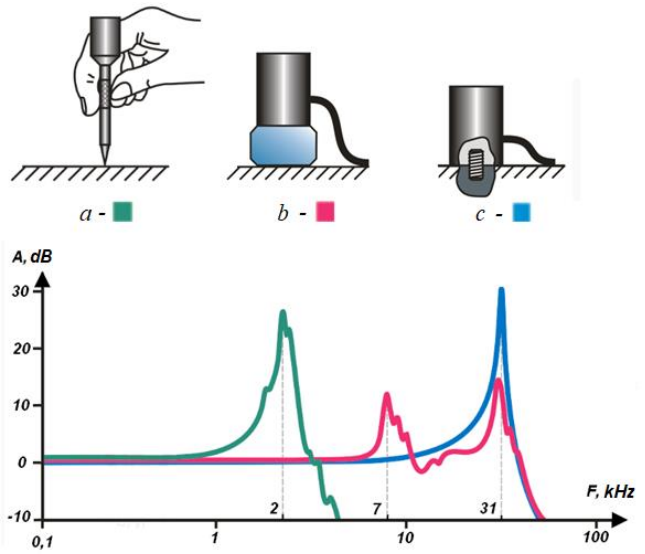


Fig. 3. Ways of fastening of accelerometers: and - by means of a manual probe of a standard design; b - mounting on a magnet; in - fastening on a hairpin

When mounted on a magnet, the resonance of the sensor depends on the strength of the magnet and the state of the contact surface, and it is usually in the range of 4–10 kHz. Despite such a low resonance in the problems of vibration monitoring with such mounting, it is possible to make relative measurements of vibration after resonance on the magnet. Moreover, relative measurements can be performed on the resonance of the magnetic mount, the quality factor of which is limited (Fig. 3), and when lubricating the surface of the object at the point of installation of the magnet, the quality factor of this resonance is further reduced. It should be noted that often only with the help of a magnet it is possible to measure vibrations in the tangential direction (when diagnosing electric motors) without any preparation of the object of control (installation on the body of corners, ledges).

If the surface is made of non-magnetized materials, the use of a manual probe is allowed, but the standard design of such a probe minimizes the resonant frequency (Fig. 3). This problem can be solved by introducing into the design of the probe an elastic element through which the accelerometer will be pressed by the probe to the object, and which will thus regulate the force of the pressure. In this case, as in the case of threaded mounting, the resonance of the accelerometer may not decrease. But the vibration sensor can be affected by vibration guidance from

the hand with which the probe is pressed against the object. To reduce these movements, it is necessary to eliminate the rigid connection of the probe and the accelerometer, as well as installing an elastic element between them.

To simplify the proposed design as much as possible, it is recommended to make the probe entirely of elastic material with the installation of an elastic gasket between the probe and the sensor (Fig. 4). It is also important to provide a mechanical isolation of the accelerometer cable with an elastic element and a probe, otherwise the guidance by hand will be transmitted through the cable.

In some cases, it is necessary to measure the vibration of the nodes of the object of control, the surface of which has a high temperature. When installing a magnet on such a surface, the heat flux is well transferred directly to the sensor housing, which distorts the results of vibration measurements (temperature jumps and the resulting thermal expansion, the sensor perceives for a long time as vibration, mostly low frequency, and until the sensor and the object of control are establish thermal equilibrium).

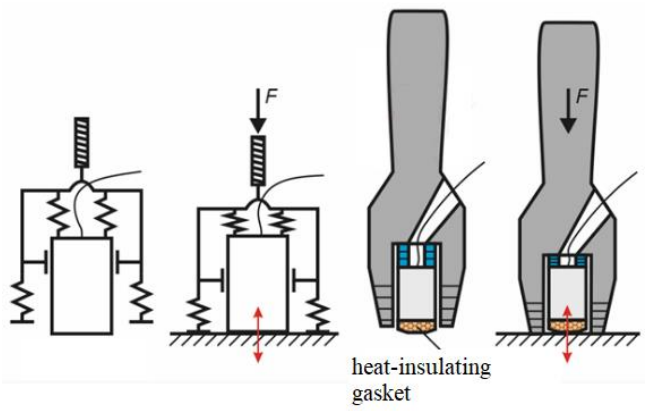


Fig. 4. Special probe design

In such cases, it is desirable to attach a rigid heat-insulating gasket, for example made of textolite, to the contact surface of the sensor built into the probe for short-term measurements.

4. Conclusion

The current state of technologies of control of machine equipment with measurement of vibration parameters is considered and analyzed in the work. All work to ensure optimal operating modes of the mechanism for monitoring, to install sensors and carry out measurements should be carried out in full compliance with the current norms and rules to ensure the safety of the work being carried out.

The recommendations for optimization of vibration control points in natural conditions of operation and after short-term operation of the mechanism in dangerous modes are formed. The methods of mounting the measuring transducer in the equipment monitoring system are considered. It is shown that in order to obtain complete information, in order to link the accelerometer measurement data with the real conditions and consequences, it is necessary to take into account the methods of mounting the measuring transducer.

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CUSTOMIZATION BASED ON CAD AUTOMATION IN PRODUCTION OF MEDICAL SCREWS BY 3D PRINTING

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Abstract: *The paper presents a proposal of a complete CAD Automation solution enabling customization of the production of medical screws to individual patient requirements. The proposed approach using OLE technology enables the introduction of customization at the CAD project stage. The assembly of the surgical screw in the PLM system is generated by means of a specially developed application. The application communicates with the SolidEdge system using an API, taking into account 10 different input parameters. Three different types of medical screws have been developed in the application: the Herbert Screw, Cancellous Screw, and Malleolar Screw with three different thread types: rectangular, isosceles, and trapezoidal. The screws designed in this way can be manufactured using 3D printing techniques or CNC machining, and can be used for both humans and animals.*

Keywords: CAD automation, customization, medical screw, 3D printing

KASTOMIZACJA OPARTA NA CAD AUTOMATION W PRODUKCJI WKRĘTÓW MEDYCZNYCH PRZY UŻYCIU DRUKU 3D

Streszczenie: *W artykule przedstawiono propozycję kompletnego rozwiązania CAD Automation umożliwiającego dostosowanie produkcji śrub medycznych do indywidualnych wymagań pacjenta. Zaproponowane podejście z wykorzystaniem technologii OLE umożliwia wprowadzenie kastomizacji już na etapie projektu CAD. Montaż śruby chirurgicznej w systemie PLM generowany jest za pomocą specjalnie opracowanej aplikacji. Aplikacja komunikuje się z systemem SolidEdge za pomocą API z uwzględnieniem 10 różnych parametrów wejściowych. W aplikacji opracowano trzy różne typy śrub medycznych: śrubę Herberta, śrubę gąbczastą i śrubę kostkową z trzema różnymi rodzajami gwintów: prostokątnym, równoramiennym i trapezowym. Zaprojektowane w ten sposób śruby mogą być wytwarzane przy użyciu technik druku 3D lub obróbki CNC i mogą być stosowane zarówno dla ludzi, jak i zwierząt.*

Słowa kluczowe: CAD automation, kastomizacja, śruba medyczna, druk 3D

Introduction

Customization is the adaptation of a product to the individual needs of a client, in this specific case a patient. Currently, standardized surgical screws with specific lengths, diameters, and thread pitches are available on the market. Until now, a partial solution to this problem has been the release of several series of a given product, the variety of which on the market is very large. This, however, does not guarantee finding a screw with whatever parameters are needed for each medical case [10].

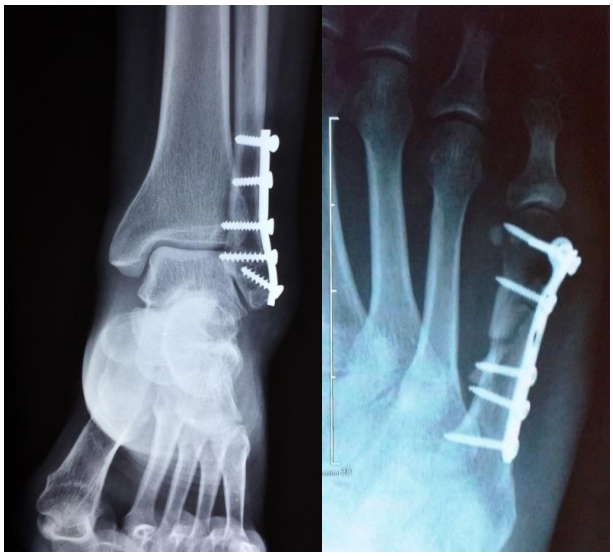

Fig. 1. Image of medical screws embedded: on the left – in a ankle; on the right – in a finger

When it comes to the length of medical screws, there is a wide variety on the market, while other parameters such as the shape of the thread and the thread pitch are not [9].

The presented solution may also be useful in conducting research consisting in selection of the parameters and shape of a medical screw based on the individual bone's properties [7]. One can imagine research in which different screws are selected for different types of bones, and their reliability and strength of embedding in the bone or pullout force [2] are examined, also in synthetic bone [11].

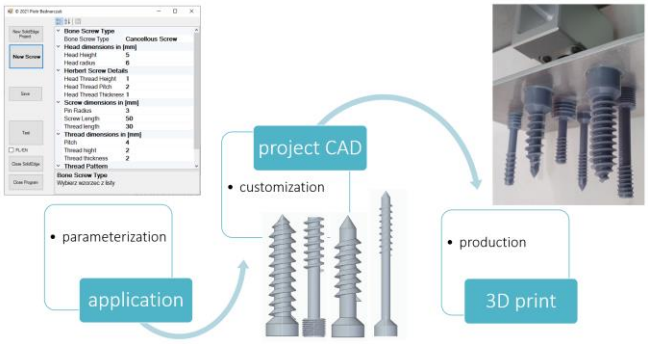

Fig. 2.Medical screw production process with customization at the CAD stage

Let us take a look at the complete process, from selecting the parameters in the specially created application, through generating the project in the CAD system, to printing the surgical screws on a 3D printer. In this experimental use case, printing in resin by the SLA method has been chosen. Of course, other medically neutral materials such as titanium can be used instead of resin, which can be printed on a metal 3D printer by laser sintering metal powders. The article focuses mainly on presenting the application of computer science in medicine, presenting a complete technological solution.

1. Customization at the CAD project stage

The process of customization itself is characteristic of hand-made products, not automatic, e.g. furniture made to individual customer orders. In mass production, the scope of customization is very limited and comes down to the configuration of the equipment of the same product, e.g. the selection of different equipment options of the car. Thus understood, customization takes place at the very end of the whole process, after the production stage.

What if we reverse the order and introduce customization at the very beginning of the production cycle, i.e. in the project stage? It is then possible to influence the parameters of the final product. Designing can also be very laborious with each individual customer order. The whole idea of this approach, however, lies in automating the customization process, means automating of creation the CAD project.

The presented solution focuses on surgical screws, of which 3 types have been selected: the Cancellous Screw, Herbert Screw, and Malleolar Screw (see figure 3). However, nothing prevents other types of screws from being implemented in the program generating the CAD projects, e.g. the Cortical Screw, the more complex Mono Axial Screw, or even the Poly Axial Screw.

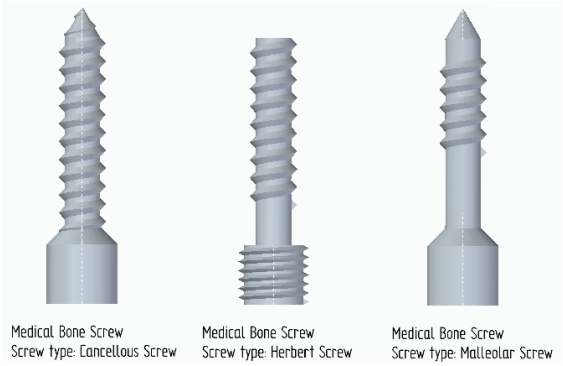

Fig. 3. Medical screw types: Cancellous Screw, Herbert Screw, Malleolar Screw

The presented customization of medical screws concerns 10 parameters, which are:

1. Bone Screw Type:
   Cancellous Screw, Herbert Screw, Malleolar Screw,
2. Screw Length,
3. Screw Diameter,
4. Pin Radius,
   Thread Pattern: rectangular, isosceles, trapezoidal (see Fig. 4),
5. Thread Thickness and Head Thread Thickness for Herbert Screw,
6. Thread Pitch and Head Thread Pitch for Herbert Screw,
7. Thread Hight and Head Thread Height for Herbert Screw,
8. Head Radius,
9. Head Length.

Fig. 4. Customization of the thread type: a – rectangular, b – isosceles and c – trapezoidal

It should be noted right away that it will not be profitable to do this for every type of product, and in some cases, it may not be possible at all. In this case – the production of medical screws – however, customization seems to be an ideal solution. The production costs of a product designed in such a way are not without significance. When using resin or metal 3D printers, however, they do not seem to be overly high [6, 8].

2. Development

In order to implement customization at the project stage, you can use CAD (Computer Aided Design) software. For this, you will need an application that controls the CAD system and generates projects in it automatically, based on the input parameters set. Such a control application should be custom-written [1].

The application would use OLE (Object Linking and Embedding) technology to communicate with the SolidEdge CAD system. Simply put, OLE is a mechanism for embedding objects in applications that allows you to control these objects using an API (Application Programming Interface). Using this technology, it is possible to create an application that controls a design support system, such as SolidEdge or another system from the PLM (Product Lifecycle Management) family, e.g. AutoCad [5, 12]. The control application for generating CAD projects in the SolidEdge system is presented in figure 5.

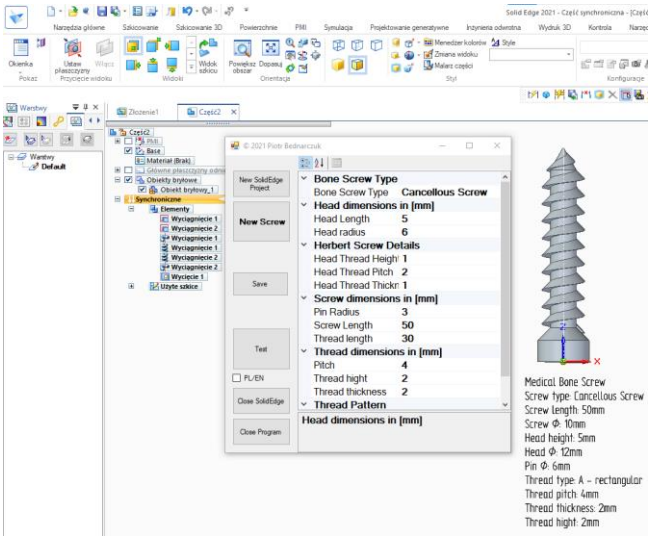

Fig. 5. Control application for generating CAD projects with a list of input parameters

The control application that we use to embed the OLE object in the CAD program can be written in any object-oriented language, such as C#, C++, Visual Basic.NET or Java [4, 5]. These objects are made available in the form of a DLL (Dynamic Link Library). Most of the producers of CAD or PLM software provide such libraries. In order to generate custom CAD projects, the following is required in the control application:

- adding a DLL library to the project
- DLL library support,
- creating an object that will be linked to the CAD system,
- calling methods of a CAD object: eg.: creating a project, drawing parts of an assembly
- converting and saving the project to a file format for 3D printing.

Listing 1 shows how to use the AutoCad OLE object in the C# programming language.

Listing 1. An example of using the AutoCad object in the C# programming language

```
try
 {
ObjectacadApp=Marshal.GetActiveObject("AutoCAD.Application");
   if (acadApp == null) return null;
 }
catch (System.Exception ex)
 {
   result = null;
 }
```

We can use the OLE object of SolidEdge in a very similar way (see listing 2). We purposely included two examples for different PLM systems, and in different programming languages, to show that the desired result can be achieved in many ways. In the following part, for better readability and understanding, the focus is on presenting listings only in one programming language – Visual Basic.NET [5].

Listing 2. Example of using a SolidEdge object in the Visual Basic.NET programming language

```
On Error Resume Next
  objApp = GetObject(, "SolidEdge.Application")
  If Err().Number > 0 Then
  Err.Clear()
  objApp = CreateObject("SolidEdge.Application")
  objApp.Visible = True
End If
```

After accessing the CAD program object, the only thing left to do is to use the methods provided by this object. First, you need

to create a project object – SolidEdge.Application – and then an assembly object – SolidEdge.AssemblyDocument – in which the assembly will be added – SolidEdge.PartDocument. This section of the program is covered in listing 3.

Listing 3. Creating assembly and part objects for SolidEadge in Visual Basic.NET

```
    objDoc = CType(
        objApp.Documents.Add("SolidEdge.PartDocument"),
        SolidEdgePart.PartDocument)
    objAssembly=
CType(objApp.Documents.Add("SolidEdge.AssemblyDocument"),
```

The complete assembly may consist of several, or several dozen elements – parts that are created by extending, rotating or cutting basic figures, i.e. a circle, a rectangle, a triangle. An example of creating such an element by extruding is the AddFiniteExtrudedProtrusion method presented in listing 4.

Listing 4. Creating an assembly element by extruding in Visual Basic.NET using the AddFiniteExtrudedProtrusion method

```
    objModel = objDoc.Models.AddFiniteExtrudedProtrusion(
            NumberOfProfiles:=1,
            ProfileArray:=objEPProfArray,
            ProfilePlaneSide:=t,
            ExtrusionDistance:=d
        )
```

To create parts by rotating, you can use the AddFiniteRevolvedProtrusion method. However, the most difficult part to develop is the screw thread. This is done with the AddFiniteBaseHelix method, as shown in listing 5.

Listing 5. Creating a screw thread in Visual Basic.NET using the AddFiniteBaseHelix method with example calling parameters

```
    objModel = objDoc.Models.AddFiniteBaseHelix(
            HelixAxis:=objBRAxis,
            AxisStart:=igStart,
            NumCrossSections:=1,
            CrossSectionArray:=objBHCSArray,
            ProfileSide:=igRight,
            Height:=0.0,
            Pitch:=s,
            NumberOfTurns:=pr * 2 * Math.Sqrt(3) / 2 / s,
            HelixDir:=igRight,
            TaperAngle:=k,
```

A project created in this way can be programmatically saved to a file in the STL (Stereolithograph) format, i.e. in the form of a triangle mesh.

3. Use cases and results

The complete custom manufacturing process for 12 different medical screws is shown as an example of use. The complete production cycle consists of 3 steps:

- customization – entering the parameters into the program,
- generating a CAD project – creating a project in the SolidEdge program,
- 3D printing – printing elements in a 3D printer, e.g. LCD-based SLA type.

In the first step, 4 different configurations were introduced for each of the 3 types of screws, and which gives us 12 different CAD projects as well as 12 completely different 3D prints. The possible combinations of these 10 customization parameters are of course endless, so the focus was on those that show the possibilities of the proposed solution and the diversity of the final product.

A Cancellous screw CAD project was generated first. The screw parameters enter figure 6.

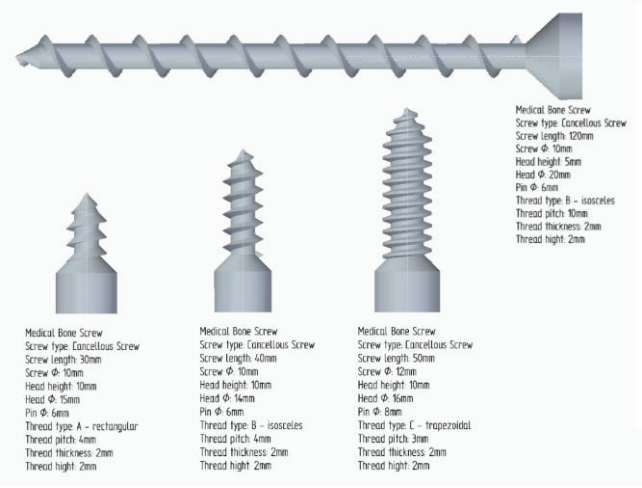

Fig. 6. Generated CAD projects of Concellous Screw

These screws were then printed on an LCD-based SLA 3D printer. It should be noted that this printout is intended to show the final effect of the complete process, but it is not made of a material used in medicine (see figure 7).

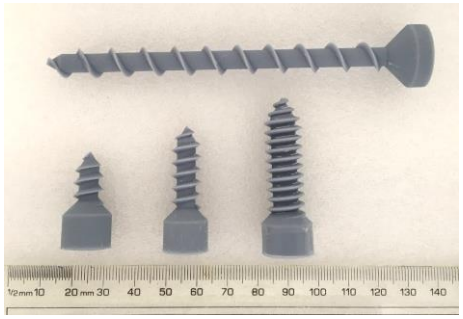

Fig. 7. 3D print of Cancellous Screws on an SLA printer

A CAD project was then generated for Herbert screws. The screw parameters entered into the program are visible directly under the drawings (see figure 8).

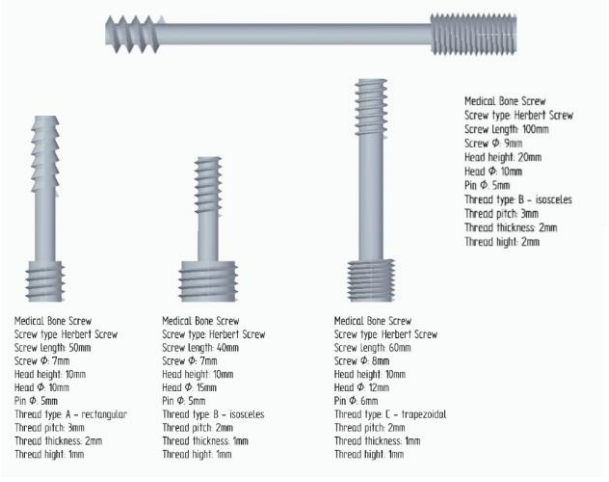

Fig. 8. Generated CAD projects of Herbert Screw

In this case, the 3D prints will look as are shown in figure 9.

Finally, a CAD project was generated for Malleolar screws. The screw parameters entered into the program are visible directly under the drawings (see figure 10).

The 3D prints will look as are shown figure 11.

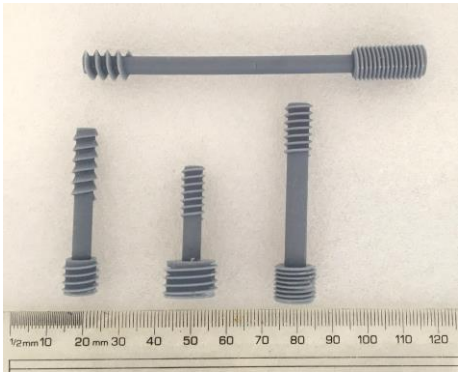

Fig. 9. 3D print of Herbert Screws on an SLA printer

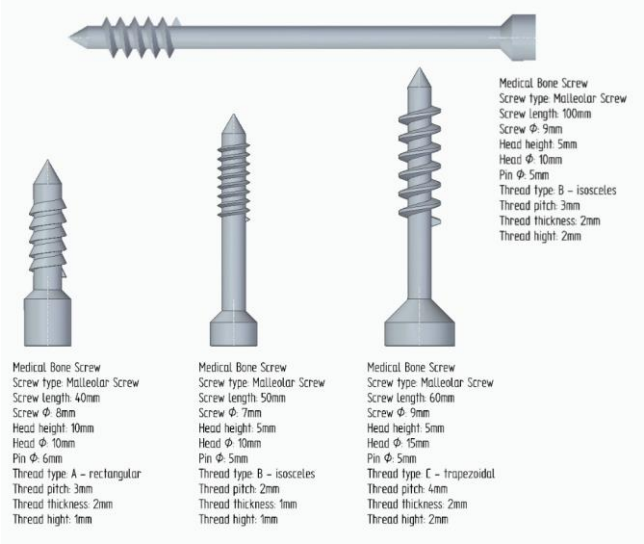

Fig. 10.Generated CAD projects of Malleolar Screw

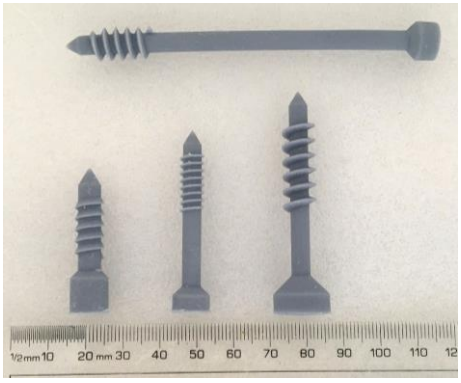

Fig. 11. 3D print of Herbert Malleolar on an SLA printer

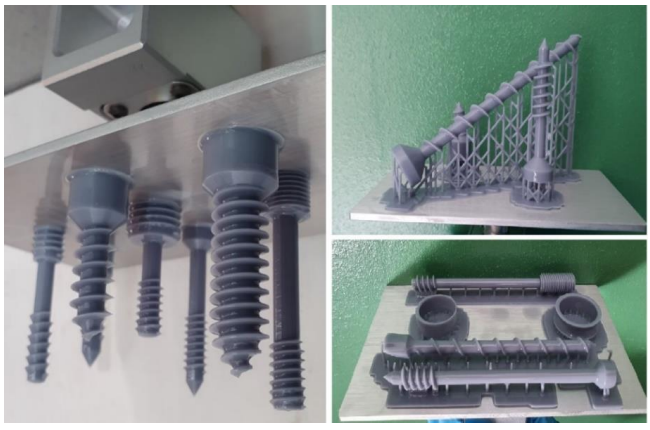

Fig. 12. 3D printer tables with various of print layouts

The time to generate a CAD project from entering the customization parameters is a few minutes. The screws were printed in 3 rounds, the shorter screws were printed vertically and the printing time was no more than 3 hours. The long screws were printed horizontally or at an angle with a support and then the printing time was about 4 hours. 3D printer tables with various of print layouts are presented in figure 12.

4. Conclusions

The presented process of customization of the production of medical screws – from parameterization, through project generation, to 3D printing – has been successfully completed. The generation of the CAD projects, including entering the input parameters, only took a few minutes. Printing with a 3D printer takes a few hours, of course, and this depends on the type of printer and material used. In this specific case, printing of all screws took no more than 4 hours. It is enough to use only the appropriate materials, e.g. titanium, so that they can be used in specific medical cases. More advanced CNC machines would also be able to manufacture such screws by machining. However, this is not the essence of this idea. The conducted research shows that customization can be quite easily transferred from the post-production stage to the CAD project stage. If we use appropriate methods of manufacturing these products directly from the CAD project, we produce almost unlimited customization possibilities. Most cases can be carried out with a standard product that is generally available on the market, but there are also medical cases for which such a method may be the only way to obtain screws with the expected parameters [3].

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METHOD AND GAS DISCHARGE VISUALIZATION TOOL FOR ANALYZING LIQUID-PHASE BIOLOGICAL OBJECTS

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***Abstract**: In the article are presented the results of researches that touch the problem of the reliability improvement of determining the impurities concentration in biological objects in liquid by using the method of gas discharge visualization. There is an improved analysis method for biological objects in liquid based on gas discharge visualization (GDV), proposed criteria approach towards the assessment of liquid bio object's composition applying this method, presented the assessment of the nature of liquid bio objects, which use the intensity of spectral components of its radiation has gotten during GDV. There is a developed and researched math model of ignition of a crown discharge and the dependency of spectrum intensity of radiation of liquid-phase biological object on its chemical composition proposed a conversion function for the assessment of the impurities concentration, together with the informative parameters of GDV images. All the results of the experimental researches of GDV and spectral composition of liquid-phase biological objects (LPBO) are presented in the article. The proposed approach lets specify the range of Mg concentrations in an oral fluid (OF) at various thyroid disorders obtained by the trilonometric method. It was found that the concentration of Mg in oral fluid of patients without thyroid disease is 12.73 ± 2.16 mg/l, patients with risk factors for thyroid disease have a concentration of 14.98 ± 1.92 mg/l, patients with sporadic goiter have a concentration of 26.65 ± 3.73 mg/l. Such data allow providing the patients with a better diagnosis of pathological disorders in glandular thyroids that are based on the concentration of Mg in oral fluid. It is confirmed that the concentration of Mg in oral fluid greater than 15 mg/l may indicate the presence of trilonometric pathology, including the focal thyroid gland.*

Keywords: gas discharge visualization, liquid-phase biological objects

METODA I NARZĘDZIE DO WIZUALIZACJI WYŁADOWAŃ GAZOWYCH DO ANALIZY OBIEKTÓW BIOLOGICZNYCH W FAZIE CIEKŁEJ

***Streszczenie**: W artykule przedstawiono wyniki badań poruszających problem poprawy wiarygodności oznaczania stężenia zanieczyszczeń w obiektach biologicznych w cieczy metodą wizualizacji wyładowań gazowych. Opracowano ulepszoną metodę analizy obiektów biologicznych w cieczy opartą na wizualizacji wyładowań gazowych (GDV), zaproponowano podejście kryterialne do oceny składu obiektów biologicznych w cieczy z zastosowaniem tej metody, przedstawiono ocenę charakteru obiektów biologicznych w cieczy wykorzystującą intensywność składowych spektralnych jej promieniowania uzyskanego podczas GDV.Opracowano i zbadano model matematyczny zapłonu wyładowania koronowego oraz zależność intensywności widma promieniowania obiektu biologicznego w fazie ciekłej od jego składu chemicznego, zaproponowano funkcję przeliczeniową do oceny koncentracji zanieczyszczeń wraz z parametrami informacyjnymi obrazów GDV. W artykule zostały przedstawione wszystkie wyniki badań eksperymentalnych GDV i składu spektralnego obiektów biologicznych w fazie ciekłej (LPBO).Proponowane podejście pozwala określić zakres stężeń Mg w płynie z ust, przy różnych schorzeniach tarczycy uzyskanych metodą trylonometryczną.Stwierdzono, że stężenie Mg w płynie z ust pacjentów bez chorób tarczycy wynosi 12,73 ± 2,16 mg/l, u pacjentów z czynnikami ryzyka chorób tarczycy stężenie wynosi 14,98 ± 1,92 mg/l, u pacjentów z wolem stężenie wynosi 26,65 ± 3,73 mg/l.Dane te pozwalają na zapewnienie pacjentom lepszej diagnostyki zaburzeń patologicznych w tyreocytach gruczołowych, które opierają się na stężeniu Mg w płynie ustnym.Potwierdza się, że stężenie Mg w płynie ustnym większe niż 15 mg/l może wskazywać na obecność patologii trylonometrycznej, w tym ogniska w tarczycy.*

Słowa kluczowe: wizualizacja wyładowań gazowych, obiekty biologiczne w fazie ciekłej

Introduction

Glándula tiroides (GT) is one of the important glands of inner secretion that is very sensitive toward the influence of outcomes of the many diseases caused by an environment state, a diet, an iodine deficit, inflectional diseases, and stresses. Bad environmental conditions in Ukraine, in particular, the Chernobyl accident, cause the number of patients with GT disorders increasing [2].

There are harmonic researches, medical ultrasound, biopsy, scintigraphy methods, thermography, X-rays, and other methods for the GT disorders diagnosis. But many of these methods very often need worthy and practically rare tools, can make a negative influence on a humane body, need significant time for implementation and the reliability of these methods on the first stage of a disease does not reach 91%. So, searching for new diagnosis methods are still actual today [3].

Any thyroid pathology (every enlargement of GT not depending on its functional state, morphological changes, and causes), in particular during focal pathology of GT (knotted struma, growth, cyst, thyroid) is followed by the growth of metal concentration (Al, Mg, Ca, Sc, Co, Cu, Zn, As, Zr, Ba) in its tissues. The concentrations of Mg and Ca is the biggest in this fluids and vividly correlate with each other because its correlation represents in-cell homeostasis and form antioxidant protection of cells, when the regulation of Ca-F-Mg change is provided, in many folds, by GT. In the first stage of thyroid diseases, the quantity of Mg in blood's plasma does not indicate the in-cell Mg deficit. So, it's worthy to use the probe of Mg rate in oral fluid for disease diagnosis on the first stage of health problems because of the strict similarity between oral liquid and in-cell liquid chemical specificities [8, 15].

The current oral fluid researches are based on applying mass spectrometry, fluorescent, potentiometric measure, luminescent, interferometric, colorimetric, etc. research methods. Let's find out the chemical and biological composition of OF, but the needed tools are still large, worthy, or need a too big quantity of chemical agents, need a too long time for analyses. So, the development of new research methods and tools for a chemical express analysis of OF composition is still an important and an actual goal [13, 14].

One of the modern express methods of the research of liquid phase biological objects (LPBO) (together with OF) is gas discharge visualization (GDV), which happens during the influencing of a biological object (BO) by an alternative (a frequency more than 1000 Hz) electromagnetic field that has a huge voltage (20-25 kV per sm) when an object starts to radiate a shine caused by a gas discharge between BO and an electrode. BO is a part of an electric circuit, so it influences the shine specificity. So, analyzing of a discharge depiction can help to determine the state of BO [11, 16].

The LPBO method has found its domain in the medical procedures of the health conditions' screening and monitoring, the quantitative methods of an assessment of stress level, and readiness to fulfill complicated professional activities, researching the characters of fluids and materials. In its devices are researched the shine radiated by human's limbs or an LPBO. Currently, there is a bunch of researches that implement GDV of different objects and have a similar biophysical approach

towards the storage of data gotten on the base of a fractal depiction analysis. It is the main difference between the GDV method and Kirlian photography because the additional computer processing and modern math methods applying are taken place. On the base of gotten data, further analysis or expert assessment is fulfilled. But in most cases, the results of researches have biases and do not present the quantitative assessment of the state of a human body.

The last decades are carried out the researches that let state the physical aspects of GDV and create the principally new classes of tools for BO and LPBO researches that apply in its works the last microelectronic and computer methods of image processing achievements. But the diagnosis potential of the GDV method is narrowed by the absence of standardization of work tools and image analysis. The similar experiments that are fulfilled by different researchers do not get the same meanings which cause the low probability of provided assessment. So, the development of a further approach of GDV implementation is still actual.

1. The main content of the work

The chemical and biological compositions of the oral fluids (OF) depend on the state of the oral space and the activities of the inner body's organs. Approximately 20% of all known proteins are residents simultaneously as in the saliva so in the blood. OF is secreted by a body with the intensity of 1.5 liters per day and, as a more dynamic organic fluid than blood, can distinctly represent all changes of a body's state. So, an analysis of OF composition by the means of the different methods lets found inappropriate states of body health and formulate a diagnosis (hepatitis, HIV, diabetes mellitus, caries, thyroid disease, etc). According to a proposed analysis of the known methods of a body's states and diseases diagnosis and on the base of the researches of the physical, chemical, and biological parameters of OF, the authors propose the classification of the known methods which are helpful in case of the diagnosis of a body's state and a healthy level and include the researches of the chemical, physical, biological parameters of OF [6]. The analysis of the biological fluids of the human body can identify approximately all diseases and the blood is a typical fluid for signalizing but the potential of oral fluids like a substance for lab testing is also very huge. It was stated that increasing of magnum concentration over 15 mg/l grade in adults' OF can be caused by the thyroid diseases or gastroduodenal illness, and it's decreasing to less than 2 mg/l grade can signify such heart diseases as an arrhythmia, tachycardia, etc. So, an analysis of OF allows put a diagnosis under the thyroid diseases, which are currently identified by the means of a palpation and an ultrasound diagnostic, and in this way hardly depends on the physicians' work experience.

So, the improvements of FBO analysis methods on the base of GDV is proposed, the criteria approach of LPBO composition assessment on the base of this method is started, the assessment of LPBO composition which applies the intensity of spectrum components of its radiation during the process of GDV is proposed, the math models of a streamer are developed, the function of impure's concentrations founding is gotten, describing the model of intensities of the central section of the normalized spectrum image together with a bunch of informative parameters of LPBO images is proposed by the authors.

The improved method of an LPBO analysis on the base of GDV uses the informative parameters of the sample LPBO and researched LPBO which are gotten simultaneously under the same internal and external conditions and in this way let's get the informative parameters for both LPBO that can be comprised without any additional corrections. The proposed method can be used as for the analysis of spectrum's compositions of LPBO radiations during possessing of GDV, so for the analysis of OF images which was gotten by the means of GDV.

The analysis of the spectrum's compositions of LPBO radiations in the case of GDV takes the researches of two LPBO samples that have concentration rates C_1 and C_2 using a GDV method under the conditions of constant parameters of the applied voltage (p, U, f) and typical frequency of the optical radiation ν_{ij}. The dependency of radiation intensity I_e on a dash concentration C in LPBO during using the typical frequency of radiation

$$I_e = (h\nu_{ij} A_{ij} a_{ij}(p, E, f))^b C^b, \tag{1}$$

where:
$h\nu_{ij}$ –photon energy, which is emitted during the quantum passing from energy state W_i to energy state W_j,
$a_{ij}(p,E,f)$ – the coefficient that indicates the number of atoms which have reached the state W_i when such work parameters as a gas pressure p, a voltage of electrical field E, a frequency of the applied voltage f are constant,
C – the initial concentration of neutral atoms,
b – reabsorbing coefficient.

The dependency of the C_2 impurity concentration on the intensity of both sample and model LPBO under the condition of the same applied voltage and the known concentration of C_1 impurity in model LPBO has the next equation.

$$C_2 = C_1 \sqrt[b]{\frac{I_{e1}}{I_{e2}}} \tag{2}$$

where I_{e1} and I_{e2} are the intensities of the model and sample LPBO radiations on the typical frequency of radiation.

The streamer's image is a superposition of partial crown streamers on a one-half period of alternated voltage or the integral image of shining of alternating partial crown streamers. The normalized streamers image is an image that takes only one streamer, the central one of which comes together with the image's center, and the brightest part of the streamer is situated on the lower part of the image. The developed math model of the streamer lets define the dependency of the mean length of streamer $\bar{l}$ on the geometrical parameters of LPBO (Figure 1), its chemical compositions and the parameters of an applied voltage

$$\bar{l} = \frac{U\sigma}{2\pi r_\kappa h e N_a \sum_{i=1}^{k} \frac{a_i m_i}{M_i}} t\left(1 + \frac{\omega\cos(\omega t)t}{\sqrt{2}}\right) \tag{3}$$

where:
r – a drop's radius;
σ – a drop's specific conduction;
h – the height of drop's edge;
e – an elementary charge;
α_i – a dissociation rate of i substance, which is a part of LPBO;
m_i – the mass of i substance, which is a part of LPBO;
M_i – molar mass of i substance, which is a part of LPBO;
N_a – the number of Avogadro;
t – the mean duration of electron avalanche's life;
U – the action significance of applied alternated voltage;
ω – the cyclical frequency of applied voltage [8].

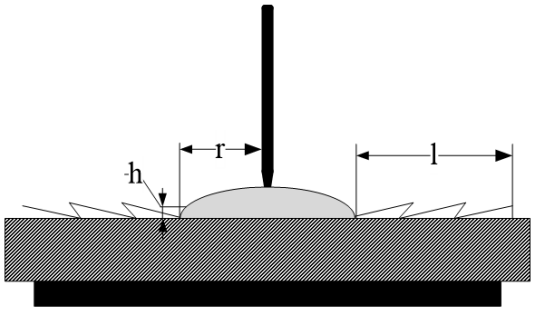


Fig. 1. The physic model of LPBO and its geometric parameters

In the graphs, 2–4 are presented the dependencies of streamer's length on the applied voltage's value, its frequency, and the molar concentration of impurities.

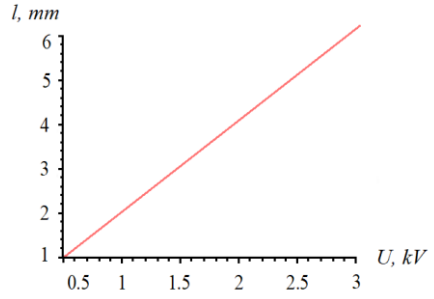


Fig. 2. The dependency of streamers length on applied voltage

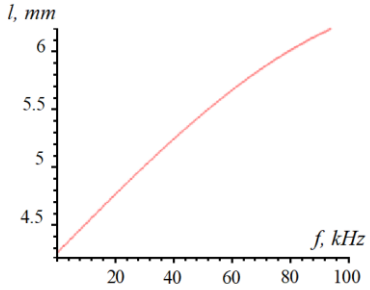


Fig. 3. The dependency of streamers length on the frequency

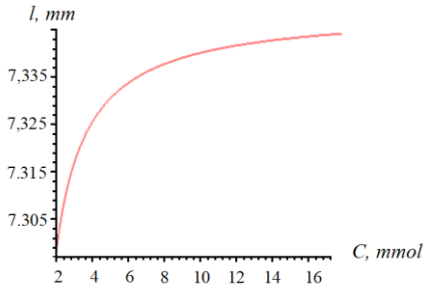


Fig. 4. The dependency of streamers length on NaCl concentration

As one can see in the graph, the dependency of a streamer's length on a voltage and frequency is linear and its dependency on a molar concentration of impurities is linear in the case of a small concentration rate [4].

As a result of experimental research works the next series of LPBO images, that have a clear picture of a streamer, is gotten by the means of GDV (figure 5).

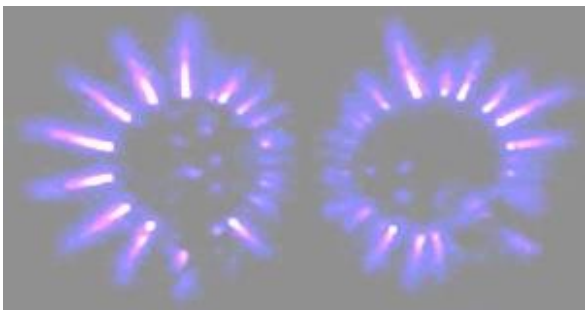


Fig. 5. The LPBO images are gotten by GDV implementing

The streamer's analysis shows that the brightness of the central section tends to increase or decrease according to an exponential low.

$$I = I_1 e^{k_1 x} \tag{4}$$

$$I = I_2 e^{k_2 x} \tag{5}$$

where I – a pixel's brightness; x – the number of a pixel from the end of the streamer (the pixel intensity of which a higher than a background), I_1 and I_2 – the optimal value of the maximal intensities of the central streamer's section for, in proportion, increasing and decreasing of streamers' brightness; k_1 and k_2 – the coefficients of increasing and decreasing of the brightness of streamer's central section.

The proposed empirical model of the distribution of the intensity of the central section of a normalized streamer's is

$$I = \frac{B}{x^3\left(\exp\left(\frac{A}{x}\right)-1\right)} \tag{6}$$

where A, B – the energetic streamer's coefficients, which are defined on the base of an approximation of the values of the central section's brightness [2].

On the base of analyzing of experimental data in addition to such informative parameters as I_1, I_2, k_1, k_2, A and B, is proposed to apply the next important parameters: I_{max} – the maximal intensity rate of streamer's central section; L_i – the pixel's quantity beginning from the first one that is over the noise level to the one that has maximal intensity I_{max}; L_s – the number of pixels on which the intensity of central section of normalized streamer's image is alternating; S_s – the mean brightness of a streamer (divide the sum of brightness of the all pixels L_i on the number of such pixels); S_i – the mean brightness of an image (divide the sum of image pixel's brightness that is over the line of noise's brightness on its quantity). All parameters instead of S_s and S_i, are defined in a section that is drawn through the symmetry that has a pixel of maximal brightness I_{max} (Fig. 6).

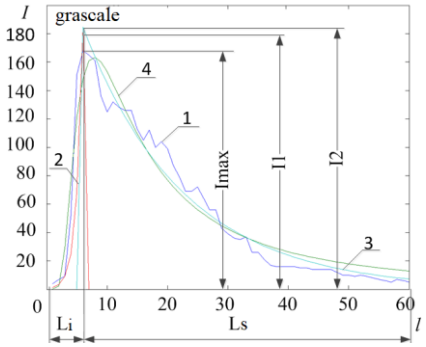


Fig. 6. The intensity distribution of central section of streamer's image and its parameters: 1 – the intensity distribution of central section: 2 – the intensity of increasing, 3 – the intensity of decreasing, 4 – the approximated characteristic

To estimate LPBO state, the complex criterion of purity is developed on the base of the proposed informative parameters

$$K = \frac{UI\tau k_1 T}{cm\Delta t k_2 AB} \tag{7}$$

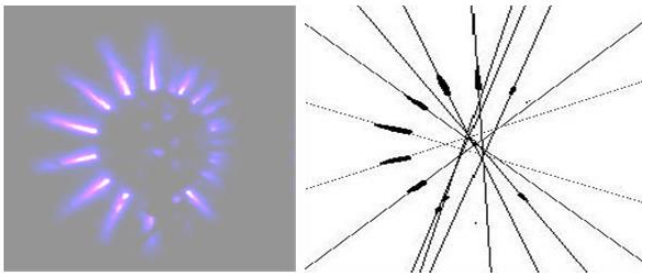
where U – a value of a voltage applied to LPBO; I – an electric current that goes through LPBO; τ – a time of voltage applying; c –specific heat of an object; m – a mass of an object; Δt – the change of LPBO temperature during a voltage applying.

The criteria access to the assessment of LPBO composition by the means of the improved method of analyzing of LPBO composition on the base of GDV using the parameters of the normalized streamers' images lets retrieve the informative parameters for both images of LPBO. Then, both can be compared without any previous correction.

To get the space distribution of streamer's brightness, the parameters of the LPBO image and the complex criteria the next method are developed and it includes the next sequence of steps:

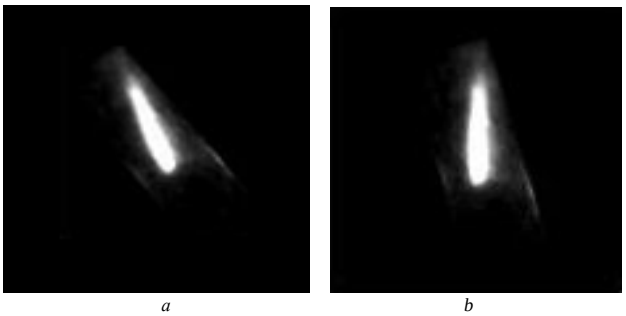
1) Preparing and setting a model and a sample LPBO in special cells of a GDV device.
2) Influencing of a charge on a model and a sample LPBO.
3) Getting of discharge image of a model and a sample LPBO by the means of GDV.

4) The division of LPBO depiction on a model and a sample images.
5) Uploading of a model LPBO image (Fig. 7a).
6) Execution of the image's threshold processing (Fig. 7b).
7) Execution the scanning of the image to find out the streamers.
8) Streamer finding.
9) Getting the equation of a line that comes through the streamer (Fig. 7b).
10) Getting an angle of a streamer's slop α according to image's.
11) Calculation of extreme coordinates to get the whole streamer inside the gotten square (Fig. 8a).
12) Setting the streamer in a vertical position (Fig. 8b).
13) Getting a data set of a streamer's intensity from the central image's section.
14) Finding the values of L_i and L_s in a section.
15) Finding the optimal value of the energetic coefficients A, B for a streamer, in which the mean square deviation has minimal value.
16) Finding the optimal value of an increasing coefficient k_1 for a section's part L_i, in which the mean square deviation has minimal value.
17) Finding the optimal value of a decreasing coefficient k_2 for a section's part L_s, in which the mean square deviation has minimal value.
18) Setting the calculated and gotten parameters in a file after which the program starts from a step 5 ad find an image of the next streamer.
19) Conduction of GDV image's analyzing by steps 4–17.
20) Getting the value of complex criterion and its comparative analysis.



a *b*

Fig. 7. The crown discharge around a drop of distilated water during the GDV: a – the income image; b – the prossessed image are gotten after the threshhold filtration and the lines that help to cut out and return the streamers



a *b*

Fig. 8. The image of a single streamer: a – the initial streamer's position; b – the streamer's position after rotation

The threshold processing of an image is carried out by the means of attribution of a zero value of intensity to pixels in which brightness is lower than zero level and attribution of a unity value of intensity to all other pixels. In that way, the binary image can be gotten. The separation of a streamer is carried out by the means of a filling function when its next extreme coordinates are defined as x_r, x_l, y_u, y_d.

According to a step 7, a line equation is composed by the means of two dots $A(x_1, y_1)$ and $B(x_2, y_2)$, through which the line is drowned (figure 7b). As a first streamer's dot the center of the closed bright area is taken, which coordinates are defined by the means of a next formula

$$x_c = \frac{\sum_{i=1}^{n} I_i x_i}{\sum_{i=1}^{n} I_i},\ y_c = \frac{\sum_{i=1}^{n} I_i y_i}{\sum_{i=1}^{n} I_i}, \tag{8}$$

where x_c, y_c – the coordinates of the center of the closed bright area, I_i – the value of brightness of a dot number i, x_i, y_i – the coordinates of i dot.

The other dot is the dot $B(x_2, y_2)$, which is situated on the maximal distance from the dot $A(x_1, y_1)$ in this closed area [6].

On the Figure 9 is shown the structural scheme of the experimental facilities for LPBO researching that lets simultaneously capture the images of a sample and a model LPBO under the equal external conditions and the parameters of experimental facilities. It is composed by two in-parallel connected core electrodes 1 and 2, that are put in cells which situated on a dielectric plate 3, and the last one in its turn is situated on the flat electrode 4, that contains a sample 5 and a model 6 LPBO in a form of a semi-sphere drops. The photo camera 7 is fixed over it and connected to the computer 8. Also, there is an in-parallel connected regulator of an impulses' quantity 9, the block of generation 10, increasing transformation 11, that is connected to electrodes 1, 2, and 4.

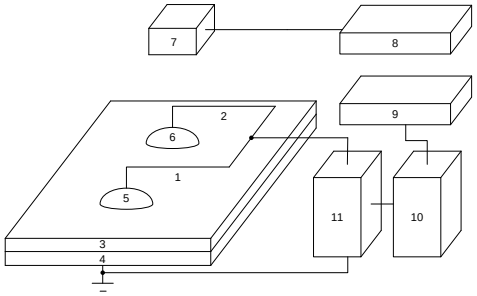


Fig. 9. The structural scheme of experimental facilities for LPBO researches based on GDV

The experimental device captures an image of a crown discharge that appears around LPBO during applying of high voltage and frequency current gotten from an increasing transformer. After this, the image comes to a computer where its main processing takes place.

During the experimental work had been defined as the next issues: the dependency of voltage's igniting of a crown discharge on its frequency and an impure's presence; the adequacy of the proposed model streamer is confirmed [5, 10].

On the Figure 10 is showed the structural scheme of the device for the spectral composition of LPBO radiation researching that works on the base of GDV and contains 1 – a high-voltage high-frequency current generator, 2 – a cell with a test LPBO, 3 – a cell with a model LPBO, 4 – an optical lens, 5 – many-channel light conductors, 6 – the outcomes of many-channel light conductors, 7 – light filters, 8 – a photodiode, 9 – amplifiers, 10 – an analog-digital converter, 11 – a digit indicator.

The device works in a next way: a test and a model LPBO are put in cells, the influence of high-voltage and high-frequency current is provided, the shine, as a result of this influence, is focused and accepted by many-channel light conductors (separately for a sample and a model object). Each channel of light conductors is ended by a light filter and after it, there is a photodiode that is connected to an amplifier and a signal from the last one go to an analog-digital converter. The digit data gotten from photodiodes are separately analyzed by the processing block for each LPBO, and then those data are compared and the results of this work are showed on the digital indicator [2].

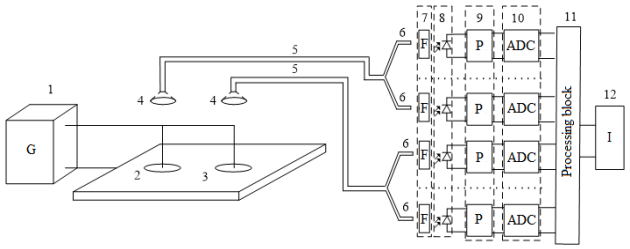


Fig. 10. The structural scheme of the device for a spectral composition of LPBO radiation researching on the base of GDV

On the figure 11 is showed the structural scheme of the experimental device for the spectral composition of LPBO radiation during GDV researching that is presented by two cells for a sample and a model LPBO, electrodes' pins 3, that is sunk in LPBO, a dielectric plate 4 between LPBO and a flat electrode 5, a frame 6, that provides a cover, a movable section 7, that lets put in a photoelectron multiplexor 10 for a test or a model LPBO, a frame for light filters fixing 9, a high-voltage high-frequency current generator 8, a section of a results' visualization 11.

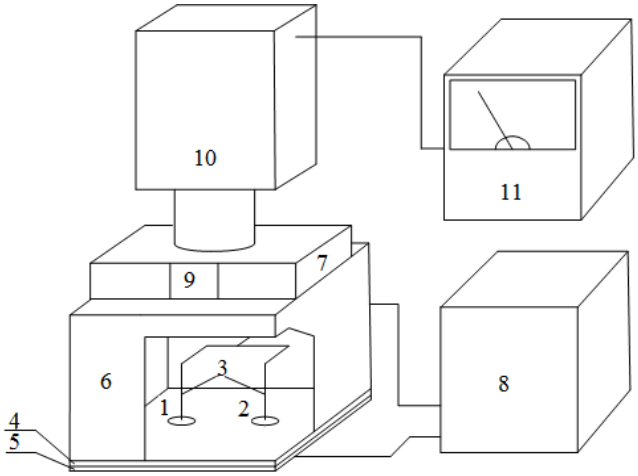


Fig. 11. The structural scheme of the experimental device for a spectral composition of LPBO radiation during GDV researching

The experimental device for a spectral composition of LPBO radiation during GDV researching works in a next way: the equal quantities of a sample and a model LPBO are put in the cells of the experimental device 1, 2; over the test LPBO photometer 7 is set by the means of a shifted section 7 and a light filter 9 ends up this construction's portion. After this, the system is ready for an influence of 3 kW 50 kHz voltages for 5 seconds. During this period the radiation intensity of LPBO is shown on an indicator 11. After this, by the means of a movable section, photometer 7 is focused on a model LPBO and the intensity of a radiation of a model LPBO is gotten in the same way. The change of light filters let's get linear spectrums of a sample and a model LPBO. The comparison of these two spectrums let's find out impure concentration in LPBO [2, 4].

On the Fig. 12 is showed the structural scheme of the GDV device for LPBO analyzing with the next new technological ideas: the use of two integral spheres that let's capture the all needed radiations from both a sample and a model LPBO and the implementing of two photodiodes for each LPBO. This new allows an increase in the preciseness of an impure concentration's assessment.

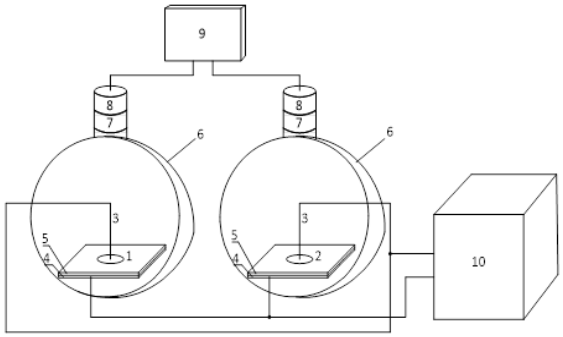


Fig. 12. The structural scheme of a device for an assessment of impure concentration in LPBO by the means of GDV principle

The device is composed by the next important elements: cells for a sample and a model LPBO– 1, 2; pin electrodes– 3, flat electrodes – 4, dielectric plates – 5, integral spheres – 6, light filters – 7, a photo acceptor – 8, processing and indicating section – 9, a generator of high-voltage high-frequency current 10.

The core element of a proposed GDV device for LPBO analysis is an integral sphere. The last one lets in the simplest way to solve the task of radiation capturing from the all body angle 4π [4].

The GDV devise for LPBO analyzing is showed on figure 13, where 1 – is a generator of a high-voltage high-frequency current, 2 – data processing and information indicating section, 3 – a photo multiplexor, 4 – an integral sphere. The scale preciseness of this device is 0.303%.

The device for identification of an impure's concentration in LPBO provides us with the spectrums of radiation of the chemical salt dissolves. Experiments are carried out in the next way: the equal quantities of a sample and a model LPBO are put in the cells; an appropriate light filter is put in; then 5 sec. influence of 3 kW 50 kHz voltage happens, during which the intensities of radiation of both LPBO samples are captured; the previous steps had been fulfilled for the other light filters. During the experimental work, 23 narrow-step light filters are used (the wide of a pass is 10 nm), which gradually covers the 457–675 nm range. On the base of gotten intensities, the linear spectrums of LPBO are formed. Such salts as NaCl, $MgSO_4$, KCl, $CaCl_2$, and FeSO4 are used during the experimental works. The distillate water is used as a model LPBO. The radiation spectrum, the spectrum of relative spectral lines of $MgSO_4$ dissolve, and distilled water are showed on Figure 14 and 15.

Fig. 13. GDV device for LPBO analyzing

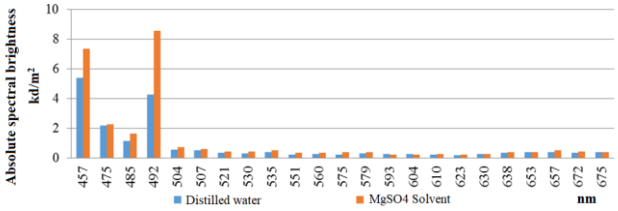


Fig. 14. The radiation spectrum of $MgSO_4$ dissolve and distillated water

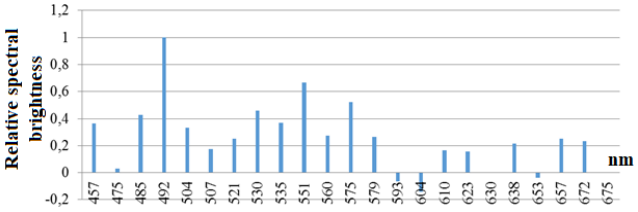


Fig. 15. The spectrum of relative spectral lines of $MgSO_4$ dissolve

On the spectrum of relative spectral lines of $MgSO_4$ dissolve the picks are presented at 492 nm, 530 nm, 551 nm, and 575 nm. The picks that are presented at 530 nm and 551 nm are caused by Mg^{2+} ions in LPBO. Analyzing the all experiments' results allows us to conclude that the maximal absolute intensities at 457 nm, 492 nm, and 485 nm waves are correlated with oxygen and hydrogen atoms. It has a maximal high because of the huge proportional quantity of water in any sample.

On the spectrum of relative spectral lines of $MgSO_4$ dissolve the pick are present at 492 nm, 530 nm, 551 nm, and 575 nm. The picks at 530 nm та 551 nm are caused by the presence of magnum ions Mg^{2+} in LPBO.

The results of conducted researches let state that identification of $Na^{1+,}$ Cl^{1-}, Mg^{2+}, Fe^{3+}, Ca^{2+} ions in LPBO by the means of the proposed device is possible [6, 12].

It had been found out that a sample of LPBO should be situated in the middle of a flat electrode to provide the best condition for exploring LPBO specificity using a mean number of all streamers or using any parameters that are based on the streamer's quantity. In the moment of a voltage applying to the LPBO sample when a bowl is absent the process of LPBO's flowing has a start with a speed that is in proportion to an applied voltage. We had been found that it's better to explore the green and red channels of the RGB image of LPBO or transform it into the grayscale. The adequacy of the model that describes a central section of a streamer depiction is checked and informative parameters are calculated. When the applied voltage is constant, the width and length of streamers depend on the impure concentration level. This dependency lets develop a screening system of LPBO based on a principle 'norm – deflection'. It had been conducted 21 experimental works when a model LPBO is a 50 mg/l dissolve and a sample LPBO is a 100 mg/l Mg dissolve. In the GDV device, the light filter with the maximal transition at 551 nm was used. The captured data let found out the absorption coefficient *b* that is equal to 0.9272.

By the means of the GDV device, the exploration of dependency of LPBO radiation's intensity on Mg concentration in LPBO was carried out. The calculated results of intensities and gotten experimental data are shown in Fig. 16. As we can see the experimental results of radiation intensity are close to the theoretical one. On the base of experimental data, it had been calculated that the experimental value of radiation intensity of explored LPBO is similar to the theoretical value of 99.04%.

It had been conducted 89 experimental works to found out the possible similarities among gotten results. During the experimental work $MgSO_4$ dissolve of a concentration 150 mg/l, or 30 mg/l Mg dissolve, was used as a model LPBO and $MgSO_4$ dissolve of a concentration 75 mg/l, or 15 mg/l Mg dissolve was used as a sample LPBO. The dissolves were prepared by the use of a chemical scale and a 100 ml flask. The results of the experiments are shown on figure 17.

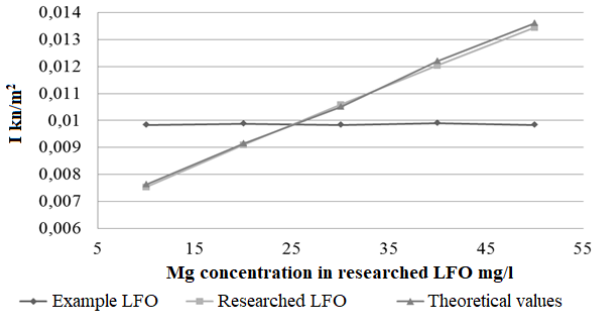


Fig. 16. The experimental specification of intensity of a test and a model LPBO together with a theoretical specification of a test LPBO

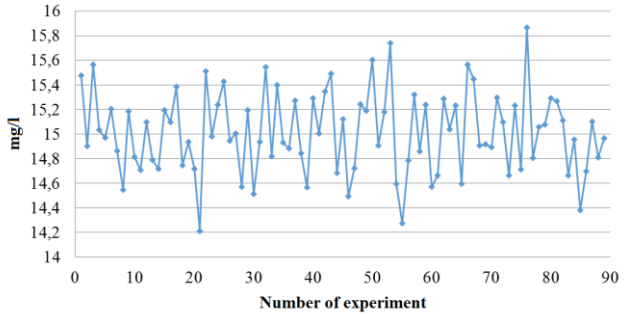


Fig. 17. Mg concentration in a sample LPBO (89 probes)

According to gotten data, the mean amount of radiation intensity of a model LPBO is 0.01058 cd/m^2, and in the case of a test LPBO, it is 0,00832 cd/m^2. Under such condition the mean value of Mg concentration in a test LPBO is 15.013 mg/l, the relative error is 1.81%.

So, the experimental assessment of the GDN device for LPBO analyzing let's conclude that the proposed technical tool matches the all previous requirements and its measurement error is lower than the measurement errors of other known tools.

To prove the dependency of Mg concentration in oral fluids on the thyroid gland's diseases the series of experiment had been conducted during the which the concentration of Mg in male oral fluid (age group 18–35 years, a sporadic goiter of 2nd stage and male group members of which have some risk factors of thyroid disease) was estimated by the means of GDV methods. The gotten data had been compared with Mg concentration in OF that was estimated by the means of the trylonometrical method. All patients were divided into three groups (20 humans in each): the first group comprises peoples with any thyroid disorders, the second group contains peoples with risk factors of thyroid disorders development and the third group was represented by the patients that have a sporadic goiter. Researching was conducted in a next way: in the morning, before feeding or teeth cleaning, every patient spits 5-10 ml of his oral fluid. After this, in the next hour, gotten samples were under researching by the means of the GDV device. As a model LPBO $MgSO_4$ dissolve of 60 mg/l concentration (or 15 mg/l Mg concentration) was used [9, 19].

Analyzing of the final results allow concluding that Mg concentration in OF of patients that do not have thyroid diseases is 12.73 ± 2.16 mg/l, an analogical indicator for the patients with risk factors is 14.98 ± 1.92 mg/l and for the third group those digits are 26.65 ± 3.73. So, in such a way the dependency of Mg concentration in OF on the thyroid diseases had been proved. Also, using GDV devices for LPBO analyzing the ranges of Mg concentration in OF of the patients from all three groups was specified [9].

The assumption that Mg concentration, that is more than 15 mg/l, can reveal the presence of thyroid pathologies (in particular, focal thyroid gland pathology – nodal goiter, tumors, cysts, and thyroiditis) had been proved. Comparing the results of the first and the third groups we had discovered that

21 patients (2 humans from first and 19 humans from third groups) had Mg concentration more than 15 mg/l, so the experiment's probability is 0.925. Gotten probability had been compared with analogical indicators of another GDV device [1, 7].

The probability of the proposed device is the highest among GDV devices and is no worse than the preciseness of other screening tools.

2. Conclusions

The work has been developed the means of GDV for LPBO that let increase the accuracy of the measurements in 1,5 times and the preciseness of impurities' concentration detection on 2.5%. It has been presented the short overlook on current GDV devices. It has been detected that during the implementation of those tools was not taken into account an influence of the atmospheric parameters (temperature, pressure, humidity) and the possible changes of in-system parameters that can make a significant influence on the gotten image. Also, the results of this researches in the many cases are biased and do not provide the quantitative assessment of a state of the human body and during the diagnosis, formation is very often used the ideas of east medical practice that do not have science confirmations. The main methods of GT are presented. The analysis of the main biological fluids of the human body is carried out and is proved that the most advanced method of diagnosis is the one based on the oral fluid analysis. It has been developed the main methods of diseases and body states diagnosis on the base of researches of physical, chemical, and biological parameters of oral fluids. The classification of methods for diseases and body states diagnosis on the base of researches of physical, chemical, and biological parameters of oral fluids are presented in the article. The worthiness of the GDV method implementation in oral fluids researches is proved. The main informative signs of LPBO images gotten by GDV implementation are presented. The methods of LPBO analyzing the base of GDV are improved by the means of simultaneous comparison researches of sample LPBO and unknown, researched LPBO, and also by the means of using a complex criterion of purity recognition of mineralization level of LPBO. It's proposed to use the intensity of spectral composition of LPBO radiation during GDV that let increase the preciseness of impurity concentration inside the researched LPBO. It has been developed the experimental facilities for LPBO researches using the GDV method and spectral intensities of LPBO radiation during GDV which are consist of two chambers for sample LPBO and unknown LPBO that let significantly compensate the possible influence of external conditions on the experiment's results preciseness. The adequacy of function between impurities concentration and the intensity of the LPBO spectral line during GDV is proved. The math model of a streamer is improved, which takes into account such parameters as a voltage, a molar concentration of LPBO impurities, a geometrical size, and conduction of LPBO. A bunch of informative parameters, which are taken from the streamer's image, is proposed and it let calculate the complex criterion of LPBO. On the base of the results of experimental researches, the empirical model of the intensity distribution of the central section of a normalized streamer's depiction is proposed. And it lets get the new informative parameters and an improved complex criterium of LPBO frequency ascertaining. The series of experiments is conducted; the dependencies of the LPBO radiation spectrum during GDV on the chemical composition of LPBO are ascertained. It is proposed to ascertain the concentration of LPBO impurities by the means of the radiation intensity of a specific spectral line of an impurity in a whole radiation spectrum of LPBO during GDV. It is established the possibility of NaCl, MgSO4, KCl, CaCl2, FeSO4 salt's ion, or its complex founding in one LPBO. The algorithm of a streamers' normalization which lets found out the streamers on the images and drives them to the stable view is proposed. It let automatically analyze streamers that accelerate the presses of informative parameters of GDV images getting and simplify further data processing and storage. The conducted experiments confirm the possibilities of an express diagnosis of GT diseases by the means of the GDV method for an LPBO analysis. It is ascertained that the intensity of researched GDV gotten by the means of LPBO impurity's concentration detector is similar to a theoretical intensity and the deviation is not more than 0.38%. The field experimental researches in a patient group, half of which has some GT disorders, are conducted using the GDV method for LPBO analysis. In this case, the probability of the research is 92.5%.

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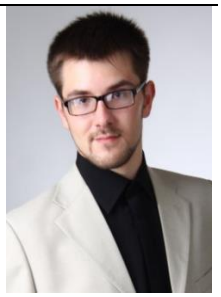

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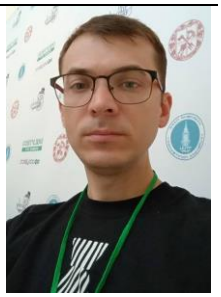

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OVERVIEW OF SKIN DIAGNOSTIC TECHNIQUES BASED ON MULTILAYER SKIN MODELS AND SPECTROPHOTOMETRICS

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Abstract. *Today, spectrophotometrics is a promising tool for non-invasive examination of the optical properties of human skin. The spectrum obtained during the study is carefully analysed by models developed by many scientists. Developed multilayer models are designed to reflect the most faithful processes occurring in the skin, its layers and essential elements. Many skin diseases are diagnosed: vitiligo, hemangios, skin birthmarks, melanoma. The article provides an overview of interesting solutions using spectrophotometrics in the process of diagnosing skin diseases.*

Keywords: multi-layered skin models, skin disease diagnosis, spectrophotometrics, spectrum

PRZEGLĄD TECHNIK DIAGNOSTYKI SKÓRY W OPARCIU O MODELE WIELOWARSTWOWE SKÓRY I SPEKTROFOTOMETRIĘ

Streszczenie. *Obecnie spektrofotometria jest obiecującym narzędziem do nieinwazyjnego badania właściwości optycznych ludzkiej skóry. Otrzymane podczas badania widma poddawane są wnikliwej analizie dzięki opracowanym przez wielu naukowców modeli. Opracowane modele wielowarstwowe mają na celu oddać najwierniej procesy zachodzące w skórze, jej warstwy i istotne elementy. Diagnozowanych jest wiele chorób skóry: bielactwo, naczyniaki, znamiona skórne, czerniak. Artykuł przedstawia przegląd ciekawych rozwiązań z użyciem spektrofotometrii w procesie diagnostyki chorób skóry.*

Słowa kluczowe: modele wielowarstwowe skóry, diagnostyka chorób skóry, spektrofotometria, widma

Introduction

Human skin is an important organ of the human body that performs many important functions in human life processes. Due to the great interest of researchers, all its properties are increasingly known. In the diagnosis of skin diseases, methods using phenomena associated with the influence of electromagnetic radiation have been widely used. Human skin consists of the main three layers in which we can distinguish absorption, refraction and scattering of light. Numerous studies [16, 24, 40] have shown that the skin contains various chromophores that absorb light in a wide range of waves, from ultraviolet to near-infrared.

Scientists have been working for many years on models of the interaction of light rays with individual skin layers [32]. Attention is paid to the type of tissue and the elements knowing in the skin, which show different properties. In [3] a model of the effects of radiation during the skin test was presented. It includes melanin and hemoglobin absorption, Mie and Rayleigh scattering, surface and subsurgial scattering, radiation reflection from subcutaneous tissue. The epidermis is the first layer of the skin that partially reflects light.

The direction of light is changed by the presence of cell membranes and organelles with different refection factors. Light in the epidermis is absorbed by melanin and dissipated further [3] Some radiation is dispersed by melanosomes. On the other hand Mie's dispersion occurs in a larger fiber of collagen and elastin, and can be directed towards a deeper layer. Subcutaneous tissue is mainly built up by bright fat cells that will reflect light. An example of the course of light rays through different layers of skin is marked in yellow in Figure 2B.

Studies of the optical properties of human skin are currently carried out due to spectrophotometrics. Based on spectrophotometric spectrum analysis [8], the transport of light through tissues for each layer of human skin can be described and its optical properties can be represented using mathematical models. Transmittance, absorption, dispersion and refinement factors, concentration of selected elements building it are also determined. For different wavelengths, maximum absorption is absorption. Many scientists are involved in determining absorption coefficients for elements that build human skin [4, 13, 19]. Figure 1 takes into account the absorption coefficient for oxyhemoglobin, water, deoxyhemoglobin and melanin. Human skin is mainly made of these elements, so it is worth paying attention to the shapes of their absorption spectrum. It is on the basis of spectre and developed models that diagnostic decisions are made [15, 17]. To receive a full diagnosis, it is necessary to know the anatomical structure of human skin, the processes of the influence of ultraviolet radiation, visible light and near infrared in each layer of the skin. It is important to have knowledge of the optical properties of the elements that build it.

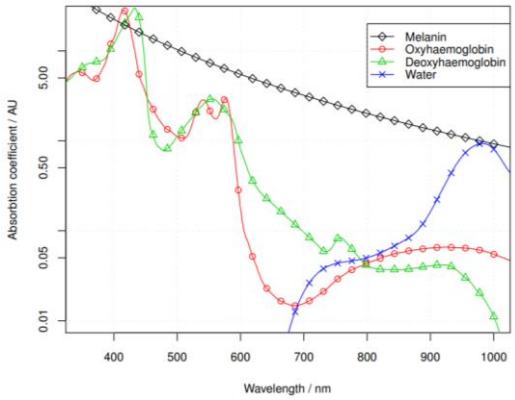

Fig. 1. Absorption factors of hemoglobin (oxyhemoglobin and deoxyhmoglobin), water, melanin [33]

1. Multilayer skin models

Scientists try to interpret optical phenomena in different ways in the skin. Many works are being created to show the ever-new properties of the elements in the skin. In addition to the number of important and different layers, models provide a lot of other information. These include melanin content, melanin absorption of useful wavelength, blood absorption from oxidized and oxidized hemoglobin [13, 17], blood volume fraction, oxygen saturation. The optical properties of a particular layer can be represented by a set of numbers of developed models. These include optical depth, single albedo dispersion, standardized volume dispersion function. It all depends on the wavelength and the type of structure.

1.1. Models 1, 2, 3 layer

Single, double and three-layer models are based on less complex assumptions about the optical properties of skin-building elements. A small number of variables are needed to use them to fully simulate models. They are useful in determining concentration, absorption coefficients of skin elements. On the other hand, they describe more accurately the optical interactions taking place in human skin. In [20] a model of two-layer leather is used, its layers are different in composition and optical properties. The top layer is an epidermis with a thickness of 50–150 μm, the next layer is dermis, which in optical terms is considered an

infinitely thick element. The volumetric absorption coefficients of epidermis and dermis, the volumetric content of melanin in the epidermis and the effect of the change in light absorption by blood vessels [2, 40] have been determined.

Figure 2A shows a two-layer leather model based on 3 layers of skin. A layer (s.i.) is included, which has properties evenly distributed throughout the layer. The components of the diffuse spectrum reflections contain information on different depths of penetration of light rays through the skin [15].

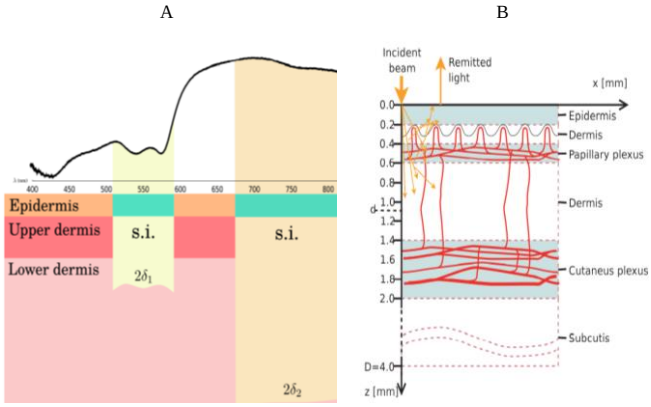

Fig. 2. Leather models created: A) double layer [4] and B)six-layer [34]

The rays of light with a shorter wavelength penetrate more superficially due to the high absorption of hemoglobin and melanin [21, 25, 38]. The author of the model determined the average depths of optical penetration through the dermis.

1.2. Models 4, 5, 6, 9 layer

More complex models contain four layers and more accurately describe the processes associated with radiation in the skin. They allow you to know the optical properties of the elements of the skin. However, they have their disadvantages. The known data are not accurate, many approxims and assumptions. In addition, they introduce many complex variables into the simulation giving errors. Many of their assumptions are based on complex simplifications and not yet fully studied and described phenomena.

The spectral spectrum is simulated by a combination of multiple methods. The Monte Carlo method was used in a four-layer model to analyze diffusion [4]. In this case, the dermis was divided into two layers - papillary and reticular skin. The authors of the paper [31] proposed using a five-layer leather model to simulate the size of the falling beam and the reflection and refraction of light at the contact between layers. In addition, a layer of superficial skin is separated from the dermis. They have different optical properties resulting from the presence of a large number of small blood vessels in it. Fig. 2B presents a five-layer model of human skin. Based on available literature [5, 12, 36], researchers are developing mathematical models. Numerous optical parameters of tissues have been determined, the most commonly mentioned are: absorption coefficient (μα), dispersion factor (μs), reoffer coefficient of the center (n), sample thickness (d) in centimeters are shown in table 1.

Table 1. Optical parameters of skin layers in a five-layer model for selected wavelengths [30]

Layer	λ [nm]	μα	μs	n	D
epidermis	337 633	32 4.3	165 107	1.5	0.01
I dermis	337 663	23 2.7	227 187	1.4	0.02
surface skin layer	337 633	40 3.3	246 192	1.4	0.02
II dermis	337 633	23 2.7	227 187	1.4	0.09
deep-seamed skin layer	337 633	46 3.4	253 194	1.4	0.06

Many scientists build skin models consisting of more layers of six, seven, or even nine. The six-layer mcml simulation leather model is used in many works [6, 28, 34]. The parameters of the model consist of values that are determined by the concentration of the most important skin chromophores. The nine-layer model of skin tissue was developed in [22] for spectral simulation using the Monte Carlo method. The necessary parameters were output for each of the nine layers in the simulation. The parameters used in the conventional three-layer model have been modified on the basis of some histological findings on the skin and reported examples. It occurs here: the stratum corneum, the epidermis layer (which consists of a granular layer, spinosum and base layer, the dermis is divided into five layers, the last is subcutaneous tissue.

In the dermis, the blood vessels are not homogeneous and the saturation of hemoglobin with oxygen must be separated. The volume and composition of the elements of the liner may also vary. By adopting different optical and geometric parameter values in each of the nine layers, you can simulate the reflectance spectrum under different conditions.

2. Non-invasive diagnosis of skin diseases

Diagnosing pigmented skin lesions in general practice is difficult. For diagnosis there are many stages and types of skin lesions, they are also located in different places on the body. There are many important characteristics for them, e.g. the presence of skin melanin, displacement of blood with erythuoma, a different collagen structure.

2.1. Diagnosis of basic skin diseases

The most commonly diagnosed skin diseases diagnosed by spectrophotometrics are warts, vitiligo, thrombosis and hemangios [1]. Scientists study various abnormalities of the skin in selected regions of the skin. In [26] diagnostics of warts, vitiligo and hemangios were taken. Fig. 3A shows the original reflectivity spectrum for the nipple and control skin along with the designated reflectivity. Similar graphs were created for vitiligo-covered skin – Fig. 3B. The intensity of light reflected from the skin with vitiligo is higher than for normal skin. Vitiligo introduces melanin-free areas on the skin that achieve maximum reflectivity. The spectrum of the test area of the skin and control spectre shall be compared using statistical analysis to detect wavelength ranges, regions with significant differences [19].

Changes in the shape of the spectrum help to distinguish between healthy and affected tissue. [13] the healing process of burns was taken into interest. Areas of skin after burn and healthy skin were compared using spectrophotometrics. The color of the restored skin became more red in people exposed to the sun and in older people, the received spectrums were significantly different from each other. Also interesting is the topic [29] of the use of spectrophotometrics in the analysis of skin color arising from the healing process of burns.

Often spectrophotometrics is not a sufficient diagnostic tool. This diagnostic technique is combined with other tools. [27] a Doppler laser is used to assess oxidation and perfusion in the oral skin. Real-time optical parameters of the skin are also used for hyperspectral imaging to obtain volumetric fractions in the blood, oxygenation of melanin content and RGB image of the skin area under test [18]. Spectroscopic studies are also used in cancer research in cancer therapy [23, 37].

Scientists use spectrophotometrics in the diagnosis of skin melanoma. The study refers to the incidence of melanoma in the bright [10] and dark-skined populations of different ages and regions of the globe. The most commonly determined parameter then is the estimation of the content and density of melanin in the skin [9]. However, to correctly recognize the disease, it is necessary to prepare well for the examination.

In [35] attention was paid to how the result of the final diagnosis is influenced by the presence of dark hair on the skin.

Fig. 4 shows the variability in melanin density in ba-given tissue, taking into account the hairy and smooth area depending on the season. Neighborhoods more likely to come into contact with solar radiation as the hand have higher concentrations of melanin in its composition.

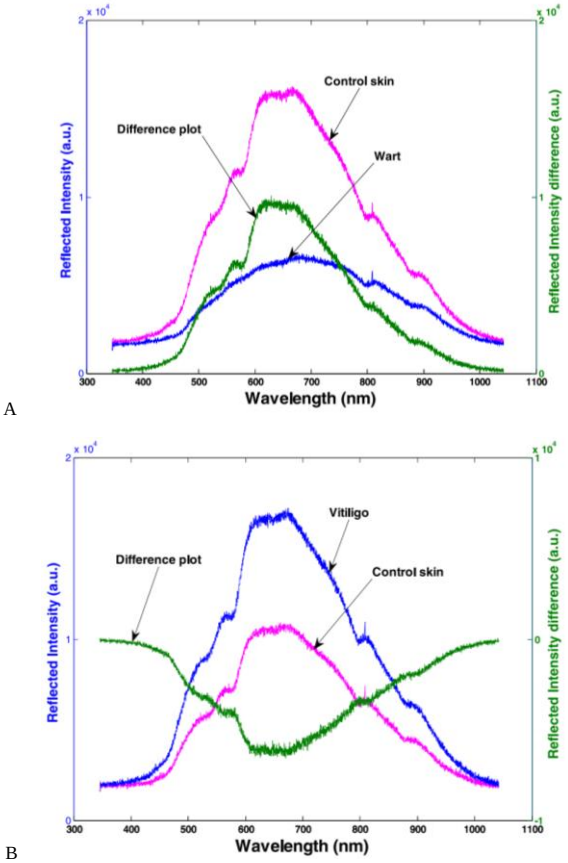

Fig. 3. Diffuse reflection spectrum and reflectivity factors for A) warts and normal skin, B) vitiligo and normal skin [26]

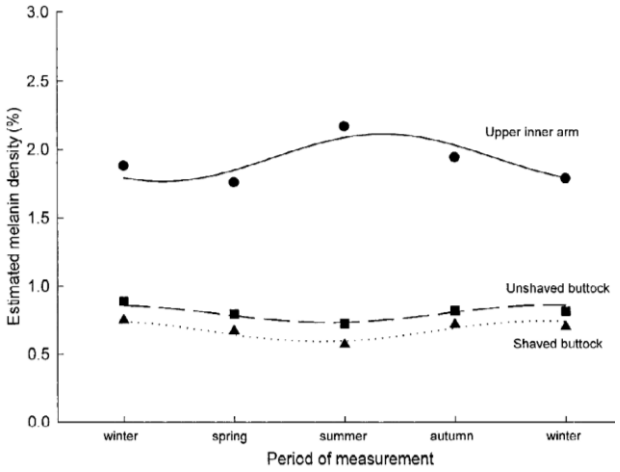

Fig. 4. Graph of melanin density changes in the upper inner arm, unshaved and shaved buttocks depending on the period of time [35]

2.2. SIAscopy

Spectrophotometric Intracutaneous Analysis (SIA) allows you to diagnose pigmented benign and malignant skin lesions. In addition, it analyzes the pigmentation of the skin with melanin, blood supply to the skin and its collagen structures [14, 39]. SIAscopy provides information about the thickness of the layers of the skin and the amount of hemoglobin, melanin and collagen in the stratum corneum and dermis.

The scans made inform about changes in the composition of the skin and ensure early detection of changes in the amount of dermal melanin. SIAscopy is equipped with a model of skin coloration, shows the relationship between the parameters that characterize the skin and its colors. Spectrum analysis, parameters determining the structure and optical properties of the skin allowed the model to be developed [15]. Melanin penetrates deep into the dermis in case of more malignant skin tumors.

SIAscope diagnoses benign lesion, malignant melanoma, keratosis and hemangioma. Fig. 5 is a set of images of replaced skin lesions [1]. They take into account the place on the patient's body and 6 characteristic resulting images. The resulting images include a dermatoscopic image, an image of the concentration of melanin in the epidermis and dermis layer, an image of hemoglobin and a picture of collagen concentrations in tissue. Images carry a lot of diagnostic information. The dark color in the image of total melanin indicates a large amount of it in the tissue. Collagen's grups are bright, and its deficiencies give darker areas in the image. However, the deficiencies of skin blood in the image suggest necrosis. Its growth on the periphery suggests the appearance of inflammation and vasodilation in the area of active tumor development [7].

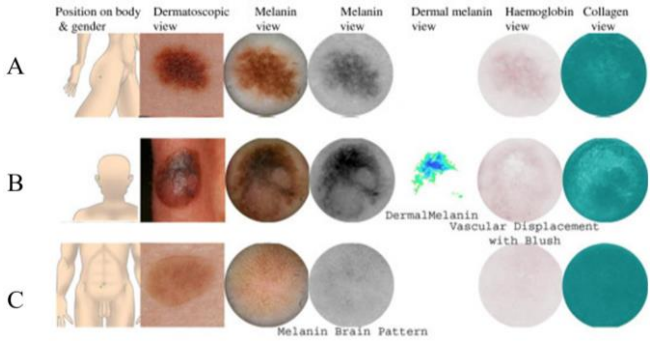

Fig. 5. Examples of images obtained from SIAscope with marked characteristics: A) mild change; B) malignant melanoma; C) seborrheic keratosis [11]

3. Conclusions

The use of skin models developed by many scientists helps to determine the presence or stage of cancer. The use of spectrophotometrics significantly reduces the use in clinics of invasive and painful biopsy for the patient. Non-invasive measurements of haemoglobin and bilirubin in the blood can be performed remotely. They do not require contact between the measuring instrument and the skin, they develop telemedicine. Human skin is a complex and organized part of the human body. Significantly different types of tissues, vessels and their function in each in layers. A closer understanding of its optical properties makes it possible to develop many diagnostic methods of its diseases.

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DYNAMIC HANDWRITTEN SIGNATURE IDENTIFICATION USING SPIKING NEURAL NETWORK

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Abstract. *The article proposes a method for dynamic signature identification based on a spiking neural network. Three dynamic signature parameters l(t), xy(t), p(t) are used, which are invariant to the signature slope angle, and after their normalization, also to the signature spatial and temporal scales. These dynamic parameters are fed to the spiking neural network for recognition simultaneously in the form of time series without preliminary transformation into a vector of static features, which, on the one hand, simplifies the method due to the absence of complex computational transformation procedures, and on the other hand, prevents the loss of useful information, and therefore increases the accuracy and reliability of signature identification and recognition (especially when recognizing forged signatures that are highly correlated with the genuine). The spiking neural network used has a simple training procedure, and not all neurons of the network are trained, but only the output ones. If it is necessary to add new signatures, it is not necessary to retrain the entire network as a whole, but it is enough to add several output neurons and learn only their connections. In the results of experimental studies of the software implementation of the proposed system, it's EER = 3.9% was found when identifying skilled forgeries and EER = 0.17% when identifying random forgeries.*

Keywords: online signature identification, spiking neural network, invariant dynamic parameters, signature recognition

DYNAMICZNA IDENTYFIKACJA PODPISU ODRĘCZNEGO PRZY UŻYCIU PULSUJĄCEJ SIECI NEURONOWEJ

Streszczenie. *W artykule zaproponowano metodę dynamicznej identyfikacji podpisów opartą na pulsującej sieci neuronowej. Wykorzystywane są trzy parametry dynamiczne podpisu l(t), xy(t), p(t), które są niezmienne względem kąta nachylenia podpisu, a po ich normalizacji – także do skali przestrzennej i czasowej podpisu. Te dynamiczne parametry są podawane do sieci neuronowej w celu rozpoznania jednocześnie jako szeregi czasowe bez uprzedniej konwersji na wektor cech statycznych, co z jednej strony upraszcza metodę ze względu na brak skomplikowanych procedur konwersji obliczeniowej, a z drugiej ręka zapobiega utracie przydatnych informacji – zwiększa dokładność i wiarygodność identyfikacji i rozpoznawania podpisów (zwłaszcza w rozpoznawaniu podpisów sfałszowanych, które są silnie skorelowane z autentycznymi). Zastosowana sieć neuronowa typu spiking ma prostą procedurę treningu, przy czym nie wszystkie neurony sieci są trenowane, a jedynie te wyjściowe. Jeśli konieczne jest dodanie nowych sygnatur, nie jest konieczne trenowanie całej sieci, ale wystarczy dodać kilka neuronów wyjściowych i uczyć tylko te połączenia. W wyniku eksperymentu programowego zaproponowanego systemu otrzymano EER = 3,9% przy identyfikacji sfałszowanych podpisów i EER = 0,17% przy identyfikacji fałszerstw losowych*.

Słowa kluczowe: identyfikacja podpisu online, pulsująca sieć neuronowa, niezmienne parametry dynamiczne, rozpoznawanie podpisu

Introduction

Signature identification is a biometric authentication method and is becoming increasingly popular for a wide range of practical applications, from fraud prevention in financial transactions to access control to closed areas. Handwritten signature analysis is one of the most common methods of identifying a person, which we often encounter in our daily lives. The signature identification by a human operator has many "weaknesses". So, the operator can evaluate only the static image of the signature, as far as it corresponds to the template of the signature. At the same time, there is a danger that a well-trained attacker may very similarly forge a person's signature, i.e. the image of the signature reproduced by the attacker will be very similar to a genuine person's signature. The widespread use of computer technology and information technology for data processing allows us to apply not only the analysis of the static image of the signature, but also the dynamic characteristics of its writing.

All methods of signature identification can be divided into 2 major groups: static (Offline) signature identification and dynamic (Online) signature identification [1, 3]. Static signature identification is based on the analysis of the signature image itself and uses a variety of methods for recognizing graphic images. It is unreliable because it is easy to falsify a peep image by stroking the existing original with carbon paper, transillumination, or by scanning or photocopying. Dynamic signature identification (DSI) is more reliable, as it provides for the analysis of the author's pen oscillation parameters when reproducing the signature. In the simplest case, such parameters of the signature reproduction dynamics can be three-time functions: two functions of changing the *X(t)* coordinate and *Y(t)* coordinates of the pen oscillations in the plane of the graphics tablet and another function, changing the pen pressure on the graphics tablet *P(t).* Even if an attacker learns to reproduce a graphically similar to the original signature, it is unlikely that he will be able to accurately reproduce the dynamics of the movements of the signature author, because it is individual to each person. Therefore, the most promising is the dynamic (On-line) signature identification. In addition, it is best suited for the implementation of modern information technology and exceeds the capabilities of the human operator in this process.

Despite a large amount of research on this topic, the creation of DSI systems with the required reliability and quality of work remains problematic. The difficulties of the practical application of various DSI information technologies are caused by the shortcomings of the phenomenon of signature formation as an object of the information process. Thus, the signature of the same person due to the natural variability of human handwriting is an unstable reproducible process and has the following disadvantages [9, 13]:

- variability of geometric dimensions (spatial scale) of different signatures;
- variability of writing time (time scale) of different implementations of the signature;
- variability of the angle of inclination of the signature relative to the sides of the tablet of different signature implementations.

In addition, the signature dynamic parameters (coordinates *X(t)* and *Y(t)*, pen pressure on the graphics tablet *P(t)*, etc.) are often converted into a vector of static features, which are then used in different types of classifiers to obtain the identification result. With this conversion of dynamic parameters into static ones, useful information is often lost, which reduces the discrepancy between genuine and forged signatures and thus reduces the reliability of identification.

The purpose of the article is to present the results of the new DSI method, which is based on the use of dynamic parameters of the signature process (without converting them into static parameters) and spiking neural networks, simplifies the process and increases the reliability of signature identification.

1. The general architecture of the proposed dynamic signature identification system

The general architecture of the proposed DSI system is shown in Fig. 1. The user performs the signature writing process on a graphics tablet, which usually gives the following primary dynamic parameters of the signature: *X* and *Y* spatial coordinates, pressure, pen angular orientations (i.e., azimuth and altitude angles), and timestamps. From these primary dynamic parameters, it is often suggested to obtain secondary (derived) parameters and use them. Such secondary parameters suggest taking the speed of change of coordinates ($v_x = dX/dt$, $v_y = dY/dt$), the acceleration of change of coordinates ($a_x = dv_x/dt$, $a_y = dv_y/dt$), as well as various discrete features, such as the number of maxima, minima, convex and concave areas, etc. [1, 3, 20]. Not all dynamic parameters are taken at the same time, but certain of their optimal sets. There are even studies comparing the informativeness of different dynamic parameters and their resistance to intrapersonal variability of signatures [4, 13].

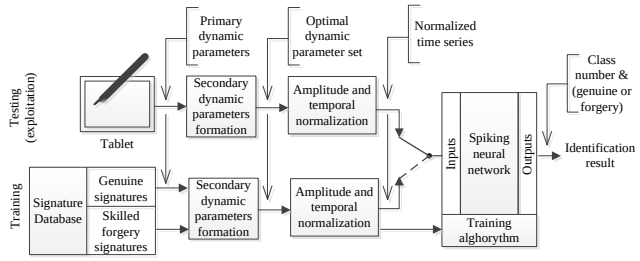

Fig. 1. Architecture of proposed dynamic signature identification system based on Spiking Neural Networks. The Spiking Neural Networks block is enlarged in Fig. 3 for a better understanding

In this study, we used a set of 3 parameters: 1) the distance *l(t)* from the current time sample of the pen coordinates (x_i, y_i) to the next (x_{i+1}, y_{i+1}) (see Fig. 2); 2) the product of the coordinates *X(t)* and *Y(t)*; 3) pen pressure on the tablet *P(t)*. These parameters were taken because they are invariant to the slope of the signature with respect to the sides of the plate [13, 14]. And the amplitude and temporal normalization [14] indicated in Fig. 1 makes these parameters also invariant to the spatial and temporal scales of a specific signature implementation and the shift of its location on the tablet field. It should be noted that the proposed method will work with other parameters and their number, but the successful choice of parameters set has a positive effect on the overall quality of the system.

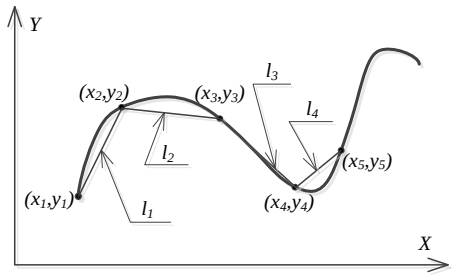

Fig. 2. Obtaining a dynamic signature parameter l(t)

After normalization, we have time series, which are sequences of digitized samples of the corresponding dynamic parameters at discrete time moments with a certain time step. These time series are fed to the input of a pre-trained spiking neural network. This is the first main difference and advantage of the proposed system, which is that the normalized dynamic parameters are fed to the spiking neural network for identification without conversion into a vector of static features, which often occurs in known systems [1, 3]. This advantage is explained by the fact that in known systems when converting dynamic parameters into static ones, a large part of useful information is lost, which reduces the reliability of identification.

The spiking neural network must be pre-trained in the task of classifying time series (dynamic parameters of the signature), so at its output, we get the result of the signature identification in the form of a class number (signatory identifier). And since the proposed spiking neural network has 2 outputs for each class (see Fig. 3), we still have information on whether the recognized signature is genuine or skilfully forged.

Genuine user signatures are used to train the spiking neural network. In principle, one genuine user signature is enough for learning, but the more genuine signatures used for learning, the more accurate the system will work. The system also provides the ability to use skilled forged signatures for training. This is optional, but also has a positive effect on the accuracy of the identification. Any database of user signatures can be used to train the system, in which the primary dynamic parameters of signatures (*X(t)*, *Y(t)* and *P(t)*) are stored. DeepSignDB [5, 20] was used in this study.

2. The structure of the spiking neural network

In the proposed method of Online signature identification, it is necessary to use namely spiking neural networks [11, 15], because they allow recognizing dynamic signals directly, i.e. without their prior conversion into a vector of static features. They also have other benefits. All the advantages of spiking neural networks over traditional neural networks are due to their neuromorphism (similarity to networks of biological neurons) and are formulated as follows:

1) recognition of dynamic patterns (language, moving images, cardiograms, dynamic parameters of the signature, etc.) without their prior conversion into a vector of static features;
2) multitasking (information about input flows circulates in a recurrent neural network and the output can be simultaneously presented the results of different tasks using different groups of readout neurons, trained to perform a respective task);
3) predictive recognition (any dynamic process can be recognized even by incomplete information about it, i.e. even before it is finished);
4) simplicity of the learning procedure (not all neurons of the network learn, but only the output reading neurons);
5) increased productivity of information processing and noise immunity due to pulse-frequency representation of information.

The structure of the spiking neural network developed in [11] was taken as a basis for Online signature identification. The modified structure of the spiking neural network for Online signature identification and recognition is shown in Fig. 3.

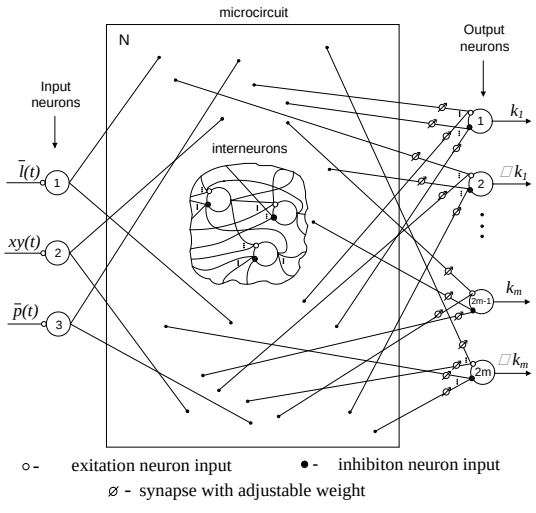

Fig. 3. The structure of the spiking neural network for online signature identification and recognition

Input spiking neurons can be constructed, for example, according to the LIF model [7]. The input neurons are fed normalized dynamic parameters of the signature *l(t), xy(t)* and *p(t)*, which are converted by the input neurons into their corresponding pulse sequences as shown in Fig. 4.

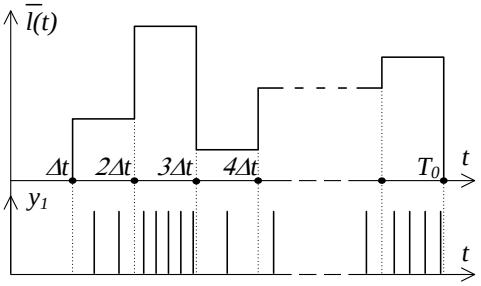

Fig. 4. Conversion of a parameter by an input spiking neuron into its output pulse signal $y_1(t)$

3. Dynamic signature identification method based on spiking neural networks

Taking into account the spiking neural network structure according to Fig. 3, as well as developed in [10] the learning rule for the spiking neural network output neurons, the principles of operation and mathematical models of spiking neurons with separate inputs [11], we can formulate a method of online signature identification and recognition using the spiking neural network.

This method is as follows:

1. Create (generate) a recurrent spiking neural network composed of interneurons in the amount of not less than $N \geq 15m$, where m is the number of classes (in this case signatures) that the network must "remember". Perform connection of neurons in the network according to neurophysiological studies [7, 15]. Choose the weights of the connections of neurons small random.
2. Generate 3 input neurons by the number of dynamic signature parameters. Connect each of them randomly with at least q neurons of the microcircuit ($n < q < N$). Choose the weights of the connections randomly.
3. Generate 2m of output neurons (2 for each template signature, first neuron to indicate a genuine signature, and second neuron to indicate a forged signature). Connect each of them randomly with at least s neurons of the microcircuit ($m < s < N$). Choose the weights of the connections randomly.
4. Apply the learning algorithm described in [10]. Only the weights of the connections of each of the 2m output neurons are adjusted. The ideal target output $k_i(t)$ can be a pulse signal with a constant (maximum) pulse frequency f_{max}, equal to the liability of the output neuron. The actual output signal *f(x(t))* will be a sequence of pulses with arbitrary time intervals between them. The input signals of the network are closer to the template signature, the higher the average for the recognition period of the pulse frequency of the output neuron, which corresponds to this template image.
5. Apply to the input of the network the investigated 3-dimensional signal (3 normalized dynamic characteristics of the signature) with duration T_0 and record which of the 2m output neurons will emit the maximum number of pulses during T_0. Namely this neuron determines the template signature, which best corresponds to the input signals of the network. The ratio of the average pulse frequency of the output neuron to f_{max} can be used as an estimate of the degree of similarity of the input signals and the template signature.

The proposed method has the following advantages:

1. The selected three dynamic parameters of the signature: *l(t), xy(t), p(t)* are invariant to the signature inclination angle, and after their normalization, even to the spatial and temporal scale of the signature;
2. Dynamic signature parameters are fed to the spiking neural network for recognition simultaneously in the form of time series without prior conversion into a vector of static features, which, on the one hand, simplifies the method due to the lack of complex computational conversion procedures, and on the other hand prevents loss of useful information. and therefore increases the accuracy and reliability of identification and recognition of signatures (especially in the recognition of forged signatures, which are strongly correlated with the genuine);
3. The result of identification and recognition can be evaluated before the end of the period of the dynamic parameters of the signature on the intense pulsing at the appropriate output (recognition with prediction), which increases the operating speed;
4. The used neural network has a light learning procedure, and not all neurons of the network are trained, but only the output ones;
5. If you need to add new signatures, you do not need to retrain the entire network completely, but just add a few output neurons and learn only their connections;
6. Noise immunity is increased due to the information coding in frequency-pulse form.

4. Experimental results

To study the performance of DSI systems, a test set is used, which includes both genuine and forged signatures, but those that were not present in the training set. Most often, the test set includes both skilled forgery and random forgery signatures, and sometimes simple forgery. Most often use one of three options. The test set includes:

1. only skilled forgery signatures,
2. only random forgery signatures,
3. both skilled forgery signatures and random forgery signatures in the proportion of 50:50.

The most interesting is, of course, the first option, because it is important to know the resistance of the system to skilled forgeries. Most DSI systems are often quite resistant to random forgeries. In this work, we used for testing 1 and 2 options.

The software implementation of the dynamic signature identification method based on the spiking neural network was carried out in the Python programming language. The TensorFlow and Keras libraries were chosen to work with neural networks in Python.

The MCYT-330 database [17], which is a part of DeepSignDB [5, 20], was chosen for the experimental study of the proposed DSI system performance. For this purpose, it would be necessary to construct a spiking neural network on Fig. 3 with the number of output neurons 660 (2 neurons for each of the 330 users of the database) and the number of interneurons not less than $330 \times 15 = 4950$ neurons. But such a network would be cumbersome to implement on a regular computer. It would take tens of hours to train it. Therefore, to accelerate the intervals of training and operation, the software of spiking neural network on Fig. 3 was implemented, which had 40 output neurons (for 20 users), 3 input neurons (for 3 dynamic signature parameters - *l(t), xy(t), p(t)*) and 400 interneurons. Simply, 12 such spiking neural networks were programmatically implemented and trained to cover 230 MCYT-330 database users selected for training. Training of one such SNN took no more than 2 hours.

The experimental protocol proposed in [5, 20] does not provide for the use of skilled forged signatures to train the DSI system. And our proposed DSI system provides such an opportunity for training. So we changed this protocol a bit. In addition, we can use more than 4 genuine signatures to train the proposed system. Therefore, changes are needed here as well.

Our protocol looks like this:

1. from the MCYT-330 database, which contains 330 users, 230 first users were selected according to the protocol [5, 20] for training and testing of our system;
2. for each user in the MCYT-330 database there are 25 genuine signatures and 25 skilled forged signatures, i.e. as a whole for selected 230 users there are 230×25 = 5750 genuine signatures and 5750 skilled forged signatures;
3. for the training of the system from every 25 genuine signatures the first 15 are chosen, and the other 10 for testing are chosen. Similarly, for training the system, out of every 25 skilled forged signatures, the first 15 were selected, and the other 10 skilled forged signatures were selected for testing;
4. thus 15×230 = 3450 genuine signatures and 3450 skilled forged signatures were selected for system training;
5. and for testing the system 10×230 = 2300 genuine signatures and 2300 skilled forged signatures were selected (testing option 1);

The results of testing the proposed DSI system based on the spiking neural network using only skilled forged signatures are given in table 1.

Table 1. Test results of the proposed DSI system based on the spiking neural network

Actual condition	Identification result	
	Signature is genuine	Signature is forged
Genuine signature (total number of genuine signatures P = 2300)	True positive – TP = 2292	False Negative – FN = 8
Skilled forged signature (total number of skilled forged signatures N = 2300)	False positive – FP = 171	True Negative – TN = 2129

We calculated the main quality indicators of the developed DSI system based on the data of table 1 when testing only on skilled forgeries – SF.

$$\text{Accuracy(SF)} = \frac{TP+TN}{TP+FP+FN+TN}\times 100\% = \frac{2292+2129}{4600}\times 100\% = 96.1\% \quad (1)$$

$$\text{Precision(SF)} = \frac{TP}{TP+FP}\times 100\% = \frac{2292}{2292+171}\times 100\% = 93.1\% \quad (2)$$

$$\text{Recall(SF)} = \frac{TP}{TP+FN}\times 100\% = \frac{2292}{2292+8}\times 100\% = 99.65\% \quad (3)$$

The F1 Score is the weighted average of precision and recall. Therefore, this assessment takes into account both false-positive and false-negative identification results.

$$\text{F1 Score(SF)} = 2\frac{\text{Recall}\cdot\text{Precision}}{\text{Recall} + \text{Precision}} = 2\frac{99.65\cdot 93.1}{99.65+93.1} = 96.26\% \quad (4)$$

We calculated 4 main quality indicators of the proposed DSI system when recognizing skilled forged signatures: accuracy 96.1%, precision 93.1%, recall 99.65%, F1 score 96.26%. To prove the achievement of the research goal, it is necessary to compare these quality indicators with the indicators of similar DSI systems [1]. This comparison is given in table 2.

Table 2 shows that the proposed system (96.1%) is better than analogs of the 1st (93.1%), 2nd (94.25%) and 5th (90.4%) rows of the table; slightly worse than the analog of the 3rd (96.5%) line. As for the 4th line, for set II (89%) our system is better, and for set I (98%) it seems worse, but in [2] it is not said how these 98% were obtained only for skilled forgeries, or only for random forgeries or both. In addition, our system and analog [2] have been studied on different databases, so the comparison may be incorrect if the complexity of signatures in the MCYT database is greater than in ATVS. Similarly, our system seems to be worse than the system in line 6 of Table 2, but again, [8] does not specify which type of forged signatures the accuracy study was performed, and the database from [8] is very small (10 + 32 people), and small signature databases usually have worse quality and complexity of signatures than large. Therefore it is necessary to compare our system with that which was investigated on the same DB and under the same (or at least similar) conditions of a choice of test signatures.

In [20], several recent developments of dynamic signature verification systems based on recurrent neural networks are considered. There are 3 approaches compared:

1. based on Dynamic Time Warping (DTW),
2. based on Recurrent Neural Networks (RNN),
3. based on Time-Aligned Recurrent Neural Networks (TA-RNN).

They are used to assess the quality of the DeepSignDB database [5, 20], where the MCYT database is included. Although these are not identification but verification systems, they can still be compared by drawing an analogy between the quality indicators of signature verification and signature identification systems.

Table 2. Comparison of quality indicators of known DSI systems with the proposed system based on the spiking neural network

	Reference	Dataset	Extracted features	Classifier	Evaluation
1	[6] 2007	SVC 2004 dataset	Basic functions, Geometric normalization, Extended functions, Time derivatives, Signal normalization	Hidden Markov Models (HMM)	6.9% (equivalent accuracy 93,1%) and 3.02% EER to skilled and random forgeries respectively
2	[19] 2011	Small dataset of 27 users	Graph theory	Graph norm	94.25% accuracy
3	[16] 2013	SVC	Wavelet transform	Neural network (NN)	3.5% EER (equivalent accuracy 96,5 %)
4	[2] 2015	Two sets of ATVS dataset are collected, dataset I contains 25 signature samples per each writer. Dataset II contains 46 signature samples per each writer	9 global features	Feed forward neural network	98% accuracy for dataset I and 89% accuracy for dataset II
5	[18] 2018	dataset consists of 10 writers with 10 genuine signatures and 10 forged signatures per each user	Extracted some features as (coordinates, pressure, altitude and azimuth) which are functions of time t	DTW algorithm was used to calculate warping distance	This system can detect fake signatures with an accuracy of 90.4%.
6	[8] 2018	Two datasets, the first dataset contains 240 signatures that were taken from ten writers and the second dataset contains 768 signatures that were taken from 32 writers	Using speed up robust features (SURF)	Support vector machine (SVM)	98.75% accuracy for the first dataset and 97.7% accuracy for the second dataset
7	Our system	DeepSignDB (MCYT-330)	*l(t), X(t)×Y(t), p(t)*	Spiking neural network	accuracy 96.1% to skilled forgeries

EER – equal error rate

Quality indicators of signature verification and identification systems are related by the formula [1]:

$$\text{Accuracy} = 100 - EER \quad (5)$$

since both EER and Accuracy take into account indicators such as FP and FN. Since for the developed system Accuracy = 96.1%, we can assume that EER = 3.9. Table 3 shows that the best value among the known systems is TARNN – 4.3%.

The quality indicators of the known systems [20] and the proposed DSI system are given in tables 3 and 4.

Table 3 shows that the developed system when testing on skilled forgeries has an EER = 3.9%, and the best known (TARNN) – has an EER = 4.3%, i.e. the developed system is better by 0.4% (absolute) accuracy than the TARNN system, and in relative units, it is (0.4/4.3)·100% = 9%. As for testing on random forgeries, Table 4 shows that the developed system has an EER = 0.17%, and the best known (TARNN) has an EER = 0.2%, i.e. the developed system has a better accuracy of 0.03% (absolute value) than the TARNN system, and in relative units, it is (0.03/0.17)·100% = 15%. In general, in relative terms, the proposed system is better than the reference system by 9% when tested on skilled forgeries and 15% when tested on random forgeries.

Table 3. Comparison of the quality (EER) of the known signature verification systems with the proposed system when tested on skilled forgeries

	Skilled Forgeries						
	1 training signature			4 training signatures			15 training signatures
	DTW	RNN	TA-RNN	DTW	RNN	TA-RNN	Proposed system
MCYT	9.1	10.5	4.4	7.2	10.1	4.3	3.9
BiosecurID	8.1	3.9	1.9	6.5	3.4	1.3	
Biosecure DS2	14.2	8.0	4.2	12.1	7.4	3.0	
eBS DS1 w1	15.3	11.4	5.4	9.3	9.0	4.3	
eBS DS1 w2	12.0	8.2	4.0	11.4	7.1	2.9	
eBS DS1 w3	14.5	14.3	5.4	12.1	11.4	4.8	
eBS DS1 w4	14.6	13.2	5.8	11.4	12.1	5.2	
eBS DS1 w5	14.9	18.9	10.6	12.9	14.0	8.0	
eBS DS2 w2	9.6	3.9	3.7	8.3	2.9	2.8	
DeepSignDB	11.2	8.5	4.2	9.3	7.9	3.3	

Table 4. Comparison of the quality (EER) of the known signature verification systems with the proposed system when tested on random forgeries

	Random Forgeries				
	1 training signature		4 training signatures		15 training signatures
	DTW	TA-RNN	DTW	TA-RNN	Proposed system
MCYT	1.2	1.1	0.6	0.2	0.17
BiosecurID	1.0	0.6	0.6	0.1	
Biosecure DS2	2.5	1.9	1.6	1.1	
eBS DS1 w1	3.2	2.5	0.7	0.1	
eBS DS1 w2	1.3	1.7	0.7	1.4	
eBS DS1 w3	0.9	1.6	0.3	0.4	
eBS DS1 w4	1.1	1.4	0.7	0.9	
eBS DS1 w5	2.7	4.1	2.1	1.4	
eBS DS2 w2	2.7	2.2	0.7	0.9	
DeepSignDB	1.8	1.5	1.1	0.6	

5. Prospects for further research

Further research can be divided into the following 2 general areas:

1. research in terms of analysis and synthesis of effective dynamic parameters of the signature and their pre-processing,
2. research in terms of finding new and improving known methods and means of classifying time series, which are the dynamic parameters of the signature.

In the course of the research, it was found that a good influence on the result of identification has a successful choice of a set of dynamic parameters of the signature, which are submitted to the classifier. It is necessary to continue the study of informativeness and variability of various dynamic parameters of the signature in the following areas:

- look for more informative dynamic parameters of the signature, having adequate metrics of informativeness,
- look for dynamic signature parameters that have low intrapersonal variability, having adequate metrics of intrapersonal variability,
- look for dynamic signature parameters that have high interpersonal variability, having adequate metrics of interpersonal variability.

The question also remains relevant: how many optimal dynamic parameters should be chosen and which ones to achieve the maximum reliability of dynamic identification of signatures at a minimum cost? On the one hand, the more parameters you take, the more accurate the system should be. But, on the other hand, processing a large number of parameters requires more computing resources and more time to make a decision. It is also not clear whether it is justified to choose a large number of parameters, as they are not all independent, as they are calculated from four primary parameters ($x(t)$, $y(t)$, $p(t)$ and $\gamma(t)$).

Therefore, the task of further research is to study the degree of influence of individual dynamic parameters of the signature on the overall reliability of the process of signature identification and justification of the optimal sets of dynamic parameters of the signature.

In the course of the research, it was noticed that the dynamic parameters of the signature are more stable in some areas (time intervals) and less stable in others. Therefore, logically, the idea arises to highlight such areas in the analysis of different implementations of the user's signature and then use only them, and not the entire signature in the identification. This possibility is provided by the metric proposed in [21] for finding the similarity of time series, which is called Longest Common Sub-Sequences - LCSS.

In terms of finding new and improving known methods and means of classifying time series, you need to pay more attention to methods that do not require the conversion of dynamic parameters into static vectors or descriptors, because it loses useful information. Such methods are methods using recurrent and spiking neural networks. Therefore, in particular, it is necessary to improve the structure and learning methods of spiking neural networks.

6. Conclusions

1. The article proposes a method of dynamic (Online) signature identification based on a spiking neural network. The structure of the network is original and uses spiking neurons with separate inputs of excitation and inhibition [11]. A feature of the network structure is also the use of 2 output neurons for each signature, first, to indicate a genuine signature, and second to indicate a skilled forged signature.
2. To represent the signature, the choice of the following three dynamic parameters of the signature is substantiated: 1) $l(t)$ – the distance between adjacent discrete signature points, 2) $xy(t)$ – the product of the coordinates $X(t)$ and $Y(t)$; 3) $p(t)$ – pen pressure on the graphics tablet. These dynamic parameters are invariant to the signature writing angle, and after their normalization even to the spatial and temporal scales of the signature.
3. The selected dynamic parameters of the signature are fed to the spiking neural network for recognition without prior conversion into a vector of static features, which simplifies the method due to the lack of complex computational conversion procedures, and prevents the loss of useful information, and therefore increases the accuracy (especially when recognizing forged signatures, which are strongly correlated with the genuine).

4. The proposed spiking neural network has a simple learning procedure. In addition, if you need to add new signatures, you do not need to retrain the entire network, but just add a few output neurons and learn only their connections. This network is also the basis of modern neurocomputer architectures [12].
5. The software implementation of the proposed method was experimentally evaluated. It turned out that the developed system when testing on skilled forged signatures has EER = 3.9%, and the best known (TARNN) has EER = 4.3%. As for random forgeries testing, the developed system has an EER = 0.17%, and the best known (TARNN) has an EER = 0.2%.

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GRANULAR REPRESENTATION OF THE INFORMATION POTENTIAL OF VARIABLES – APPLICATION EXAMPLE

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Abstract. *With the introduction to the science paradigm of Granular Computing, in particular, information granules, the way of thinking about data has changed gradually. Both specialists and scientists stopped focusing on the single data records themselves, but began to look at the analyzed data in a broader context, closer to the way people think. This kind of knowledge representation is expressed, in particular, in approaches based on linguistic modelling or fuzzy techniques such as fuzzy clustering. Therefore, especially important from the point of view of the methodology of data research, is an attempt to understand their potential as information granules. In this study, we will present special cases of using the innovative method of representing the information potential of variables with the use of information granules. In a series of numerical experiments based on both artificially generated data and ecological data on changes in bird arrival dates in the context of climate change, we demonstrate the effectiveness of the proposed approach using classic, not fuzzy measures building information granules.*

Keywords: granular computing, information granules, knowledge representation, fuzzy clustering, ecological data

ZIARNISTA REPREZENTACJA POTENCJAŁU INFORMACYJNEGO ZMIENNYCH – PRZYKŁAD ZASTOSOWANIA

Streszczenie. *Wraz z wprowadzeniem do nauki paradygmatu obliczeń ziarnistych, w szczególności ziaren informacji, sposób myślenia o danych stopniowo się zmieniał. Zarówno specjaliści, jak i naukowcy przestali skupiać się na samych rekordach pojedynczych danych, ale zaczęli patrzeć na analizowane dane w szerszym kontekście, bliższym ludzkiemu myśleniu. Ten rodzaj reprezentacji wiedzy wyraża się w szczególności w podejściach opartych na modelowaniu językowym lub technikach rozmytych, takich jak klasteryzacja rozmyta. Dlatego szczególnie ważna z punktu widzenia metodologii badania danych jest próba zrozumienia ich potencjału jako ziaren informacji. W niniejszym opracowaniu przedstawimy szczególne przypadki wykorzystania innowacyjnej metody reprezentacji potencjału informacyjnego zmiennych za pomocą ziaren informacji. W serii eksperymentów numerycznych opartych zarówno na danych generowanych sztucznie, jak i danych ekologicznych dotyczących zmian dat przylotów ptaków w kontekście zmian klimatycznych, demonstrujemy skuteczność proponowanego podejścia przy użyciu klasycznych, a nie rozmytych miar budujących ziarna informacji.*

Słowa kluczowe: obliczenia ziarniste, ziarna informacji, reprezentacja wiedzy, grupowanie rozmyte, dane ekologiczne

Introduction

The problem of the correct selection of the model form (its type and recipe) is still an open problem, widely commented on in the world of science [2, 14, 19, 20]. Well-known approaches with an established reputation [6, 7] do not always perform well in comparison with modern machine learning techniques [16, 22]. One of the key issues, apart from the choice of the model form, is the proper selection of explanatory variables for the model. This issue has a huge impact on the entire course of building the model. There are a number of recognized techniques for selecting variables for the model [5, 8]. This problem is considered in many fields of science, such as ecology [9, 25], biology [15] and economics and sociology [1, 23]. However, most of these approaches propose specific, dedicated methods of selecting variables for a specific problem and model.

The main goal of this work is to design a method that enables the storage of information about the potential of individual variables included in a larger set of explanatory variables for the model. Therefore, the key challenge is to develop a method that stores as much information as possible in a readable manner. Moreover, it is assumed that this method is universal and independent of the analyzed issue. To solve this problem, we use an innovative concept of information pellets. The idea of building information pellets was born at the end of the last century, but in recent years it has been experiencing a renaissance [3, 4, 11–13, 18]. The results contained in the study are a crisp counterpart to the fuzzy theory presented in [13].

The work is organized as follows. The second part describes the proposed solutions. The third part presents two examples of the application of the proposed innovative solution. The final part contains conclusions and directions for future work.

1. Description of information potential granules

With a the set of $\boldsymbol{N}$ variables $\boldsymbol{X_1, X_2, X_3, \dots, X_N}$, each of which can be used as a potential explanatory variable in the model describing the selected variable, the potential usefulness of each of these variables should be determined. In the classical theory of model construction, a number of methods are used to select explanatory variables for the model. Our goal is to introduce a new representation of knowledge about the information potential of individual variables in an innovative way as information granules represented by numerical vectors.

In general, the information potential granule of each variable is a vector of the form:

$$[\omega_1 : \phi_1(X_1, X_2, X_3, \dots, X_N); \dots; \omega_k : \phi_k(X_1, X_2, X_3, \dots, X_N)] \quad (1)$$

where $\omega_i, 1 \leq i \leq k$ is the number of variables meeting the variable dependency criterion, while

$$\phi_i\ (X_1, X_2, X_3, \dots, X_N\ ), 1 \leq\ i \leq\ k \quad (2)$$

returns the numbers of variables for which the variable dependency criterion is met. The value of k represents the number of methods examining the relationship between the variables. Here, a separator ":" increases the transparency of the record by separating the number of result variables from their numbers. The variable dependency criterion can be any rule describing the relationship between the analyzed variables.

The basic criterion that is usually considered when checking whether the variable X_i is suitable for describing the variable X_j is the correlation between them. It is obvious that this classic approach should also be included in the proposed method for which information representing knowledge about how many variables (among all variables considered) and with which variables it is strongly correlated for a given variable X_i. In addition to the classic correlation for the variables themselves, it is also advisable to verify the increments of which variables are correlated with each other.

In addition, depending on the specifics of the analyzed variables, it is possible to add further components to the granule of information potential of the analyzed variable. For example, when individual variables describe similar phenomena, it is possible to determine how many and which variables always assume smaller (correspondingly larger) values than the analyzed variable. In many practical aspects, when analyzing complex data, it is important to know how nominally the corresponding values of the compared variables differ. Therefore, it is reasonable to specify the number and indices of variables whose values are in the channel determined by the variable values increased and decreased by a given value.

With information potential granules it is possible to build a network of relationships between individual variables, with the strength of the relationship between two variables dependent on the number of granule components for which both variables are related.

The course of action of the proposed innovative method of building granules of variable information potential is presented in Fig. 1.

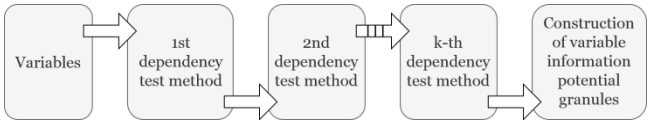

Fig. 1. Scheme of construction of information potential granules

2. Case study

The process of creating information granules in accordance with the described scheme of the construction of information granules is presented on examples of generated data and empirical data describing the arrival dates of migrating birds.

2.1. Generated data

Let us consider a set of 8 variables describing the values of a certain phenomenon changing over time. The values of the generated data analyzed are presented in the Table 1.

Table 1. Generated data

t	X1	X2	X3	X4	X5	X6	X7	X8
0	20	19	22	7	17	17	40	47
1	24	23	23	10	21	22	45	49
2	30	28	28	16	25	33	56	59
3	32	33	15	21	30	22	45	33
4	32	37	26	20	35	33	56	55
5	22	42	14	8	39	11	34	31
6	28	47	26	15	44	29	52	55
7	34	52	12	21	48	21	44	27
8	19	57	25	7	52	19	42	53
9	21	62	11	9	57	7	30	25
10	33	67	14	22	61	22	45	31
11	17	72	11	3	65	3	26	25
12	32	77	24	19	69	31	54	51
13	23	82	21	12	74	19	42	45
14	15	87	16	4	79	6	29	35
15	28	92	27	14	84	30	53	57
16	29	96	27	18	89	31	54	57
17	26	100	16	15	93	17	40	35
18	20	105	14	8	98	9	32	31
19	23	110	12	11	103	10	33	27
20	19	115	24	7	107	18	41	51

Now, let us consider the first variable i.e., X_1. The variables X_4, X_6 and X_7 are strongly correlated (Pearson's linear correlation coefficient values greater than 0.75) with this variable (see Fig. 2).

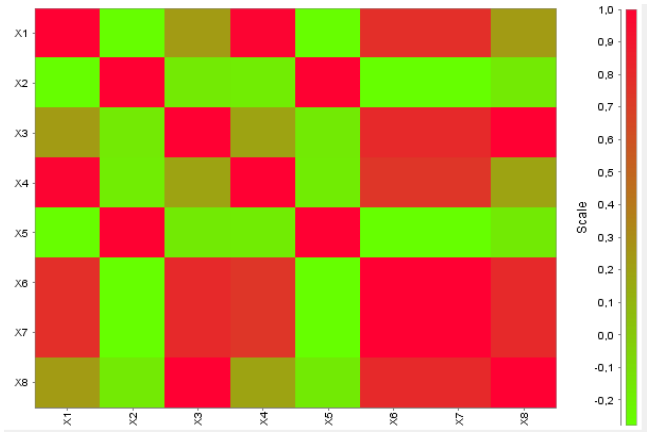

Fig. 2. The Pearson's linear correlation coefficient between variables X1 – X8

Figure 2 shows a heat map of the correlation between the different variables. As can be seen, according to the scale described in the figure, there are both strong relationships (red) and no correlation (green) between the analyzed variables.

In addition, if we determine the increments of individual variables and calculate the correlation of variable increments, we will notice that the same variables are strongly correlated with the X_1 variable, except that the values of correlation coefficients are slightly different from the original ones.

One of the easiest ways to determine linguistic descriptors that describe the behavior of variable values at different times is to use intervals based on basic statistical measures such as mean $(\bar{X})$ and standard deviation (s), or alternatively the median and quarter deviation. Examples of ranges of values and identifiers of individual descriptors with their descriptions are presented in Table 2.

Table 2. Examples of linguistic descriptors

Descriptor	Identifier	Range of values
Significantly less than typical value	-2	$(-\infty; \bar{X} - 1.5s]$
Slightly lower than typical value	-1	$(\bar{X} - 1.5s; \bar{X} - 0.5s]$
Typical value	0	$(\bar{X} - 0.5s; \bar{X} + 0.5s)$
Slightly larger than typical value	1	$[\bar{X} + 0.5s; \bar{X} + 1.5s)$
Significantly larger than typical value	2	$[\bar{X} + 1.5s; \infty)$

In the analyzed example, only one variable X_4 has values always smaller than the variable X_1, while X_7 takes higher values in all cases. In addition, the variables that differ (at any time) from the variable X_1 by at most 15 are variables X_4 and X_6.

On the individual components of the vector describing the information potential we have: linear Pearson correlation of individual variables, linear Pearson correlation of variable increments, linear Pearson correlation of linguistic descriptors. In all these cases, the numbers of the variables for which the coefficient exceeds the value of 0.75 are listed after the colon. Then, the numbers of variables for which values are always smaller than the considered variable (fourth coordinate of the vector), numbers of variables with values always greater than the variable under consideration (fifth coordinate) are listed, and finally the numbers of variables differing at each position by at least 15.

Therefore, based on the above considerations, for the variable X_1, the information granules describing its potential, according to formula (1), takes the form:

$$X_1 = [3{:}\,4{,}6{,}7;\, 3{:}\,4{,}6{,}7;\, 1{:}\,4;\, 1{:}\,4;\, 1{:}\,7;\, 2{:}\,4{,}6].$$

After conducting analogous considerations for the remaining variables, we obtain the following granules of variable information potential:

$$X_2 = [1{:}\,5;\, 0;\, 1{:}\,5;\, 2{:}\,4{,}5;\, 0;\, 1{:}\,5];$$
$$X_3 = [3{:}\,6{,}7{,}8;\, 3{:}\,6{,}7{,}8;\, 3{:}\,6{,}7{,}8;\, 0;\, 2{:}\,7{,}8;\, 1{:}\,6];$$
$$X_4 = [1{:}\,1;\, 1{:}\,1;\, 1{:}\,1;\, 0;\, 5{:}\,1{,}2{,}5{,}7{,}8;\, 1{:}\,1];$$
$$X_5 = [1{:}\,2;\, 0;\, 1{:}\,2;\, 1{:}\,4;\, 1{:}\,2;\, 1{:}\,2];$$
$$X_6 = [4{:}\,1{,}3{,}7{,}8;\, 4{:}\,1{,}3{,}7{,}8;\, 3{:}\,3{,}7{,}8;\, 0;\, 2{:}\,7{,}8;\, 2{:}\,1{,}3];$$
$$X_7 = [4{:}\,1{,}3{,}6{,}8;\, 4{:}\,1{,}3{,}6{,}8;\, 3{:}\,3{,}6{,}8;\, 4{:}\,1{,}3{,}4{,}6;\, 0;\, 0];$$
$$X_8 = [3{:}\,3{,}6{,}7;\, 3{:}\,3{,}6{,}7;\, 3{:}\,4{,}6{,}7;\, 3{:}\,3{,}4{,}6;\, 0;\, 0].$$

As it can be seen, the variable X_2 has a much lower potential than the variable number 1, which is confirmed by the smaller number of variables entering the relation with variable 2. The variables that seem to have the greatest information potential are 6 and 7. It remains an open question to decide which of these variables is more useful. Partial answer to this question comes from the analysis of the network of relationships between the variables.

The network of relationships for variables from the case considereds would look like the one presented in Fig. 3.

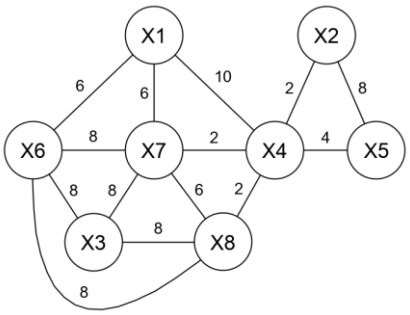

Fig. 3. Dependence network based on granules of variable information potential

Analyzing the network of connections from Fig. 3, we notice that there are the most links between variables X_1 and X_4, while the variable X_5 is in fact directly related only to the variable X_2.

The variables with the greatest total potential are X_6 and X_7 . However, the variable X_7 seems to be the variable with the greatest potential for use in building models that reflect the behavior of other variables, although this variable is not suitable for modeling variables X_2 and X_5.

2.2. Analysis of birds' first arrival dates

Modern climate changes affect many animal species, including birds. One of the issues widely discussed in the scientific literature related to the birds' response to climate change are shifts in the dates of spring arrivals and their ecological consequences [24]. However, to analyze such phenomena in historical terms, an appropriate indicator is needed. For a migratory bird species which is absent from a location for some of the year, the simplest phenological measure is the earliest report of its return, i.e., the first arrival date (FAD) [17]. Recording FADs has long appealed to human nature and it has been possible to extract historical data providing information on phenological changes expanding back two centuries [17]. Recently, annual compilations of local or regional bird records have begun to include this information as standard [17]. In this paper we used the FADs of 79 species of birds collected in northern Poland (the North Podlasie Lowland: 21°51′–23°57′ E; 52°17′–53°54′ N) in the years 1996-2016 [10, 21].

We will analyze 26 variables describing the arrival dates of birds (26 different species) [10] in close migration in the years 1996–2016. The names of individual analyzed species along with the assigned variable numbers are presented in Table 3**.**

First arrival dates for individual species are presented in table 4.

As in the case of generated data, we assume that the criteria for relationships between variables can be a correlation calculated directly for variables, correlation of annual increments, correlation for descriptors based on the mean (according to the formulas presented in Table 2), correlation of arrival weeks (instead of the day of the year, the weeks of arrival are considered and the correlation is calculated for them), incoming species always before the analyzed species, arriving always after the analyzed species, species for which the difference in arrival times does not exceed 3 weeks. All correlation coefficients with the acceptance threshold as significant equal to 0.7.

Then, following similar considerations as in the previous point, we can obtain the list of individual components of the information granules, based on formula (1), which is presented in table 5.

It shoud be noted that some variables (bird species) seem to have greater potential to describe other variables at first glance. In order to increase the transparency of the analysis of the obtained results, a heat map (see Fig. 4) was developed, which clearly shows the relationships between individual variables (bird species).

Table 3. Species names of closely migrating birds that have been analyzed

Variable index	English name	Latin name
1	Eurasian bittern	Botaurus stellaris
2	Marsh Harrier	Circus aeruginosus
3	Lapwing	Vanellus vanellus
4	Wood Pigeon	Columba palumbus
5	Eurasian blackcap	Sylvia atricapilla
6	Black Redstart	Phoenicurus ochruros
7	Spotted Crake	Porzana porzana
8	Common Redshank	Tringa totanus
9	Common snipe	Gallinago gallinago
10	European serin	Serinus serinus
11	Woodlark	Lullula arborea
12	Coot	Fulica atra
13	Great crested grebe	Podiceps cristatus
14	Red-necked grebe	Podiceps grisegena
15	Common Chiffchaff	Phylloscopus collybita
16	White wagtail	Motacilla alba
17	Dunnock	Prunella modularis
18	Reed Bunting	Schoeniclus schoeniclus
19	Eurasian penduline-tit	Remiz pendulinus
20	Eurasian Skylark	Alauda arvensis
21	Eurasian Woodcock	Scolopax rusticola
22	Black-headed gull	Chroicocephalus ridibundus
23	Song Thrush	Turdus philomelos
24	Meadow Pipit	Anthus pratensis
25	Western Water Rail	Rallus aquaticus
26	Common Crane	Grus grus

Table 4. First arrival day for individual species in 1996–2016

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22	X23	X24	X25	X26
1996	108	88	45	62	115	56	114	70	78	87	61	85	80	84	96	67	97	61	118	44	70	49	66	61	89	59
1997	85	90	53	61	119	83	105	87	72	114	60	91	92	122	112	70	111	56	122	43	89	57	55	53	92	59
1998	82	57	45	84	108	90	101	79	85	100	61	51	84	91	95	86	94	53	95	47	79	54	67	74	96	53
1999	91	82	63	80	114	82	116	79	79	88	63	65	79	88	87	75	82	63	88	59	90	63	61	78	116	65
2000	85	68	44	71	109	75	101	73	84	108	73	68	68	84	98	73	85	47	84	42	89	63	84	73	98	57
2001	100	76	40	91	98	82	93	75	69	94	71	73	76	91	90	69	92	48	91	40	76	69	69	70	94	59
2002	75	71	51	75	107	84	105	76	72	79	69	70	80	88	92	41	85	47	80	34	49	48	71	72	111	56
2003	106	81	52	71	109	88	107	82	71	82	70	74	80	103	102	75	96	70	95	67	51	71	70	71	103	66
2004	91	79	73	76	99	89	107	77	73	101	80	77	79	91	89	77	82	77	87	67	79	72	73	73	97	73
2005	86	78	73	81	98	84	100	83	83	93	69	83	85	100	91	78	87	72	90	74	91	76	75	72	102	72
2006	94	84	81	83	101	83	105	84	82	93	77	85	89	97	91	83	92	82	95	64	90	83	77	83	92	78
2007	80	66	60	51	101	62	101	66	66	86	61	67	84	93	85	66	83	64	88	48	72	64	62	66	72	61
2008	75	74	55	53	100	60	104	69	67	79	52	60	80	94	87	69	86	58	90	48	60	66	63	64	81	68
2009	75	78	58	69	96	89	97	71	73	86	69	58	81	92	91	73	81	70	92	47	79	58	60	70	97	69
2010	80	79	59	66	94	79	89	82	79	86	71	75	65	88	85	56	82	75	87	45	83	62	64	66	107	55
2011	75	79	59	66	94	79	89	82	79	86	71	75	65	88	85	56	82	70	87	45	83	62	60	66	107	55
2012	83	68	56	72	98	73	81	75	72	87	69	71	59	77	82	76	85	64	79	52	74	56	63	60	98	56
2013	100	96	65	87	96	89	104	83	96	103	95	81	89	104	99	66	97	65	102	39	100	49	63	96	107	62
2014	67	63	46	69	67	88	87	65	67	82	63	60	85	82	104	48	68	45	58	46	72	34	100	58	82	43
2015	76	80	54	53	109	80	94	74	68	86	67	79	74	79	85	53	83	53	88	53	64	62	67	67	76	53
2016	85	79	56	71	101	83	101	79	79	91	69	74	80	91	91	71	85	62	90	47	79	62	67	71	97	57

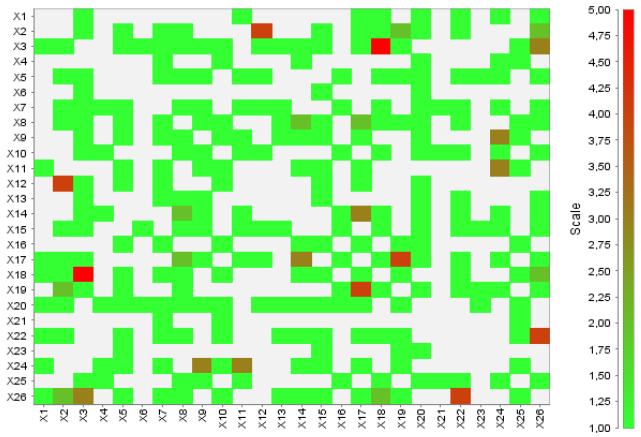

Fig. 4. Heat map presenting the network of connections between variables (species)

Analyzing the results presented in Fig. 4, it should be noted that among the considered species of birds are those that potentially very well describe the arrival times of other species. The pairs of variables between which there are no relations described above are marked in white. For the variables between which there are relationships, the colour scale presented in Fig. 4 was used. The red colour marks the variables between which there is the largest number of the relationships under consideration. The species that has the greatest potential for explaining other species is "*Lapwing*" (saved as variable X_3). This species has an information potential of 23 and is associated with 17 other species. In addition, "*Lapwing*" is strongly associated with "*Reed bunting*" (variable X_{18}). The information potential between these species is 5, i.e. for five different methods of testing relationships between variables there is a significant relationship between these variables (species). Other potentially good explanatory variables (species that characterize other species well) are the variables X_{17}, X_{18} and X_{26} (i.e. "*Dunnock*", "*Reed bunting*" and "*Common crane*"). In turn, variables with the lowest information potential are the variables X_4, X_6, X_{21} and X_{23} (i.e. "*Wood pigeon*", "*Black redstart*", "*Eurasian woodcock*" and "*Song thrush*"). These species do not have a lot of common features with other species, and therefore they will relatively rarely be used in the construction of behavioral models of other species.

3. Conclusion and future works

In this study, we have considered an emerging paradigm of information granules to establish the granular information potential of the variables. We have thoroughly examined the proposed method using the set of information about migrating birds to find the dependencies between the ways various species behave. The results of numerical experiments have shown the potential hidden in the method. Future directions of the studies may cover, among others, an application of fuzzy set-based techniques to build information potential granules as well as other than fuzzy works with uncertainty in the data. Moreover, it would be worth examining the method utilizing datasets containing more complex information, e.g., that coming from logistics, weather forecasting, or financial datasets containing time series.

Table 5. The components of information granules describing the potential of individual

Variable index	Correlation	Increment correlation	Descriptor correlation	Week correlation	Always before	Always after	Channel
1	0	0	1:17	0	7:3,11,18,20,22,24,26	0	0
2	1:12	4:8,12,19,26	1:19	1:12	5:3,18,20,22,26	4:5,7,15,17	1:12
3	2:18,26	2:18,26	1:18	1:18	0	15:1,2,5,6,7,8,9,10,12,13,14,15, 17,19,25	2:18,26
4	0	0	0	0	1:20	4:7,10,14,25	1:24
5	1:19	1:23	0	0	12:2,3,8,9,11,12,16,18,20,22,24,26	0	1:7
6	0	0	0	0	2:3,20	1:15	0
7	0	0	0	0	15:2,3,4,8,9,11,12,13,16,18,20,21,22,24,26	0	1:5
8	0	4:2,14,17,19	0	0	5:3,18,20,22,26	7:5,7,10,14,15,17,25	2:9,13
9	1:24	2:11,24	0	0	2:3,20	7:5,7,10,14,15,17,25	3:8,13,24
10	0	1:21	0	0	12:3,4,8,9,11,12,16,18, 20,22,24,26	0	0
11	1:24	2:9,24	0	0	0	8:1,5,7,10,14,15,17,25	1:24
12	1:2	1:2	0	1:2	2:3,20	5:5,7,10,15,17	1:2
13	0	0	0	0	4:3,20,22,26	2:7,15	2:8,9
14	1:17	2:8,17	0	0	11:3,4,8,9,11,16,18,20, 22,24,26	0	1:17
15	0	0	0	0	15:2,3,6,8,9,11,12,13,16,18,20,22,23,24,26	0	0
16	0	0	0	0	1:20	8:5,7,10,14,15,17,19, 25	0
17	2:14,19	3:8,14,19	1:1	1:19	12:2,3,8,9,11,12,16,18,20,22,24,26	0	2:14,19
18	1:3	2:3,26	1:3	1:3	0	11:1,2,5,7,8,10,14,15, 17,19,25	3:3, 22, 26
19	2:5,17	4:2,8,17,23	1:2	1:17	7:3,16,18,20,22,24,26	0	1:17
20	0	0	0	0	0	18:1,2,4,5,6,7,8,9,10, 12,13,14,15,16,17,19,23,25	0
21	0	1:10	0	0	0	2:7,25	0
22	1:26	0	1:26	1:26	0	12:1,2,5,7,8,10,13,14, 15,17,19,25	2:18, 26
23	0	2:5,19	0	0	1:20	1:15	0
24	2:9,11	2:9,11	0	0	0	9:1,5,7,10,14,15,17,19,25	3:4, 9,11
25	0	0	0	0	12:3,4,8,9,11,16,18,20,21,22,24,26	0	0
26	2:3,22	3:2,3,18	1:22	1:22	0	12:1,2,5,7,8,10,13,14,15,17,19,25	3:3, 18, 22

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INFLUENCE OF A PLATFORM GAME CONTROL METHOD ON A PLAYER'S EFFECTIVENESS

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Abstract. *The aim of this research is to check which of two devices the keyboard or the controller – has a positive effect on a player's game-play in a platform game. Four parameters are defined: death count, error count, game time, learning time. A custom game is designed and implemented specifically for the research. The conducted experiment is divided into thirty-minute sessions, during which one player participates in the game after getting acquainted with the game's mechanics. After completing the game, he/she fills out a survey in which he/she can express his/her level of satisfaction while using the assigned device. Each player has only one attempt. 16 players agree to participate. They are divided into two groups of 8 people each. Participants in the first group use the keyboard while those in the second group use the controller. In order to determine final results for the tested devices, the AHP method is used. The importance values for all pairs of measured parameters are determined in order to calculate their priorities. The priorities allow for distinguishing important from less important parameters. For this purpose, a survey of experienced players is conducted. They help to identify parameter importance. After trials and analysis of responses from the game-play satisfaction and parameter importance surveys, it turns out that players using the keyboard achieve better results, and the keyboard is more satisfying to use.*

Keywords: keyboard, controller, gameplay, interface, control

BADANIE WPŁYWU STEROWANIA GRĄ PLATFORMOWĄ NA EFEKTYWNOŚĆ ROZGRYWKI

Streszczenie. *Celem badań było sprawdzenie, które z dwóch urządzeń służących do sterowania postacią w zręcznościowej grze platformowej, klawiatura czy kontroler, wpływa pozytywnie na wyniki rozgrywki gracza. W tym celu zdefiniowane zostały cztery parametry: liczba śmierci, liczba błędów, czas gry, czas nauki. Badania polegały na ukończeniu gry zaprojektowanej i zaprogramowanej specjalnie na potrzeby badań. Badania zostały podzielone na trzydziestominutowe sesje, podczas których jeden gracz brał udział w rozgrywce po wcześniejszym zapoznaniu się z mechanikami gry. Po ukończeniu gry wypełniał ankietę, w której mógł wyrazić swój poziom satysfakcji z korzystania z przypisanego mu urządzenia. Na każdego gracza przypadała jedna próba wykorzystująca klawiaturę lub kontroler. Do badań zgłosiło się 16 osób, które zostały podzielone na dwie grupy badawcze po 8 osób. Uczestnicy z pierwszej grupy korzystali z klawiatury podczas badań, a osoby z drugiej – z kontrolera. Aby wyznaczyć wyniki końcowe dla badanych urządzeń, dzięki którym można było je ze sobą porównać, zastosowana została metoda AHP. Na potrzeby tej metody należało określić przewagi pomiędzy wszystkimi mierzonymi parametrami, aby obliczyć ich wagi. Wagi te przyczynić się miały do wyróżnienia parametrów ważnych od mniej ważnych. W tym celu utworzona została ankieta skierowana do doświadczonych graczy, którzy pomogli w określeniu tych przewag. Po przeprowadzeniu badań i analizie odpowiedzi z ankiet dotyczących satysfakcji z rozgrywki oraz przewag parametrów, okazało się, że gracze korzystający z klawiatury otrzymali lepsze wyniki, a klawiatura była bardziej satysfakcjonująca w użyciu.*

Słowa kluczowe: klawiatura, kontroler, rozgrywka, interfejs, sterowanie

Introduction

The method of controlling a video game character is an important aspect of designing a video game. A player's satisfaction depends upon how comfortable he/she feels while playing. Confusing keys or remembering a large number of key combinations may annoy the player or cause fatigue after only a few minutes of game playing. This can result in a sudden loss of interest in the game. It is also important what device the player uses to control the game. It can be a keyboard, alone or in conjunction with a mouse, or a special controller designed specifically for a given game.

Conducting research on players is necessary to identify the best or most convenient way of controlling what is happening in a video game. By surveying players, one can also learn what "intuitive" control is, i.e. what way of controlling the game is the easiest to remember and to learn. Players with experience in some game genres have specific reflexes that make it easier for them to adapt to a game from a new environment.

There is much discussion about which of the two game control devices – keyboard or controller – is best suited for specific game genres. The aim of this paper is to test a player's efficiency while playing an arcade platform game using these devices. Efficiency in this context can be understood in many ways and depends upon many different factors. However, by making specific assumptions based on our own experiences and the opinions of experts, one can try to calculate the efficiency factor.

Research presented in this paper addresses only one aspect of video games, but it can help to improve the quality of games overall by concentrating on this aspect. By comparing multiple game plays in which different devices are used, it is possible to draw conclusions that can help game developers make better decisions. Thanks to concrete results and strict analysis, the gaming industry can gain the additional knowledge it needs to create better products.

1. Literature review

This research is divided into the following problems:

1. Preparation of initial surveys for test participants and experts in the field of platform games.
2. Preparation of software (platform game) for conducting the research.
3. Conducting a final survey for test participants concerning the experiment.
4. Analyzing the results.

For each of these problems, a literature review is carried out, the conclusions of which are presented in subsections 1.1–1.3.

1.1. Literature overview on the preparation of initial surveys and an analysis of results

In [5] poker player bias was investigated. The authors separated research participant groups by experience. People who had played poker regularly and for at least a year were considered experienced poker players. The regularity of playing poker was defined as a minimum of once a week. Beginners, on the other hand, were defined as people who had had contact with the rules of poker but had no personal experience with the game.

In [2], drivers were divided into groups by experience. Experience was measured by the time during which a person had contact with driving a vehicle. The median experience of inexperienced drivers was 2.7 months, experienced drivers 7 years, and older drivers 38 years.

Taking into account the conclusions from the above works, the level of player experience can be determined by the time frame in which they had contact with games.

To clarify which games fall into the platform game category, game genres should be defined. [1] deals with the classification of video game genres, with "platform game" being considered a sub-genre extending the genres described in the aforementioned

study. Video games can be described by different categories, such as "action platformer" or "first-person shooter". Over the years, game genres have evolved, but platform games are always associated with 2D controls. This means that all game genres with this trait can be considered to be platform games.

In surveys prepared for the purpose of our research in this paper, examples of games of each genre (Adventure, RPG, Shooter, etc.) are taken into account when determining a player's experience. It is assumed that the game controller is limited to two directions of movement – horizontal and vertical. Additionally, titles from the arcade games category are also be preferred in this survey.

Thanks to a survey with well-defined questions, it is be possible to distinguish between experienced and inexperienced players. In order for the parameters tested during the experiment to be reflected in the real world, after defining them, they should be assigned weights that allow for distinguishing between important and less important parameters.

The method that enables such classification is called the AHP (analytic hierarchy process) method and is described in [9]. In the survey process, respondents, who are experienced players, determine which parameters they consider to be important. According to the aforementioned work, parameters will be compared to all other parameters in pairs. The respondent chooses an integer number between 1 and 9 to indicate how important a given parameter is compared to another. Thanks to this, the weight of the parameter can be calculated and converted into the final result. Thanks to this method, various parameters can be taken into account. The result of the analytical hierarchy process is one number denoting the result for the tested alternative.

1.2. Literature overview on software preparation

In [14], the authors created a platform action game in a short time using the four-step method: preproduction, production, testing and postproduction. The game was programmed in Unreal Engine. Finally, players testing the game were surveyed to answer three questions: "Is the game graphically attractive?", "Is the game playable?" and "Is the game satisfactory?". The survey results suggest that the game was missing some elements and appeared to be underdeveloped, but despite the fact that it was created in a short time, it looked attractive and was fun to play.

In order to properly design a game level, its most important elements should be defined. This was done in [11], which describes the following level elements: 1) a platform – an object on which the game character can walk/run, 2) an obstacle – an object or phenomenon that interferes with the player's achievement of a goal, 3) a movement aid – an object that helps the player to move from one point to another, such as a springboard, 4) a collectible item – an object to be collected by the player (to get extra points for example) and 5) a trigger – an object that changes the state of a level (for example a lever that opens a door). The skillful use of such elements will allow for creating a game level that is fun and intuitive for the player.

Deals with the topic of programming computer games from a practical standpoint in the Unity environment. It is addressed to programmers who don't have experience with the Unity engine and C# language. It describes the basics of game development, C# programming, project export and principles of operation of objects available in this engine [6].

In [8] the importance of correct key assignments and design of the game interface are outlined. The authors state that the player should not be forced to think how to perform a given action, but instead should focus on the problem presented in the game (e.g. on a puzzle to be solved). The unintuitive interface can frustrate a player when performing basic activities. This confirms the importance of the problem researched in this paper.

The topic of interface intuitiveness was discussed in [13], in which the author defined what the spectrum of a user's knowledge is. For the interface to be intuitive, it should be designed in such a way that the user can perform the operation he/she wants without outside help. The spectrum of knowledge should include a so-called current knowledge point and target knowledge point. These points indicate at what level of knowledge the user of the system may be. Between these points, there are levels of knowledge of a future user which must be considered when designing the interface. Usually, the interface designer focuses on the current knowledge point in order to fully adapt the interface for use by the least knowledgeable users.

In [3] an experiment was carried out in which two players and two computers with artificial intelligence play a platform game similar to "Infinite Mario Bros" (a platform game). The following parameters were selected to determine the effectiveness of the players' gameplay: completion time, last life game play duration, percentage of time spent running left, percentage of time spent running, number of jumps, number of unsuccessful jumps, number of collected coins, number of kicked shells, number of deaths caused by falling into a hole, number of deaths caused by enemies, number of killed enemies, number of enemies killed by a kicked shell.

While testing the satisfaction of players in using game controllers in a video game developed for the purpose of [15], members of the research group were asked to play a given game for 15 minutes. They had the option of extending this time by 10 minutes. 70% of the surveyed players showed a willingness to extend the game time. This may mean that this type of experiment should take from 20 to 30 minutes.

In [7], researchers created a game that adjusts its difficulty level to the player's level of focus and performance. The very low difficulty level of the game causes low player interest, and the high difficulty level can be frustrating and cause him/her to quit playing. From the results of the experiment it can be concluded that, with five levels for a player to complete where consecutive levels become more and more difficult, the greatest level of focus and performance of a player was achieved on the second level. This means that the game should be easy but also present a moderate challenge to the player.

1.3. Literature review on preparing the final survey and results analysis

In order to obtain significant results of the final survey on user satisfaction, it is necessary to carefully prepare the questions and possible answers for the players to choose from. This topic was discussed in [10], which describes the way in which the users can assess a tested solution. Satisfaction with transparency, efficiency and similar traits can be described using one of seven options to choose from. The first three options define a given element in a negative way, with the first option being extremely negative. They can be specified as -3, -2, and -1. The fourth option, specified as 0, means that the user does not think about the tested solution either in a negative or a positive way. The last three options, specified as 1, 2 and 3, express a user's positive opinion of the tested solution with the last option being extremely positive. The questions asked of the user should concern:

1. appeal (general impression of the product);
2. clarity (is it easy to learn to use the product?);
3. efficiency (can the user use the product without much effort?);
4. reliability (does the user fully control interaction with the product?);
5. stimulation (is the use of the product satisfactory?).

Quoting the introduction to [12] "A recent trend in the video game industry is toward a more complex controller. Devices such as the Dual Shock 2 controller, made popular with the Playstation 2, are designed to satisfy the needs of the avid gamer but can be intimidating for nongamers to adopt". This means that people who do not have experience with video games may be more inclined to play with the keyboard they are already familiar with from working on a computer, as opposed to a controller which is intended only for playing video games.

In [4] experiments were carried out to prove that controllers with Oculus Touch motion sensors are more intuitive than an Xbox game console controller in the case of VR games. A strategy game and an FPS (first-person shooter) game were used in the

experiment. It turned out that, according to obtained results, the intuitiveness of the controllers, the sense of presence and the player experience for both controllers differed only slightly, thereby negating the initial thesis. Despite the different results for both controllers, they were not significant enough to prove a thesis that initially seemed correct.

2. Research methods

The AHP (Analytic Hierarchy Process) method mentioned in subsection 2.1 was used to calculate the final results for the tested alternatives (keyboard and controller). For this purpose, it was necessary to define criteria by which these alternatives could be described. The criteria (also referred to as parameters) are defined as follows:

- Death Count (DC) – the number of deaths of the player's character during the game.
- Mistake Count (MC) – the number of times the player pressed an incorrect button (button not assigned to any action in the game).
- Game Time (GT) – the time in which the player completed the game.
- Learn Time (LT) – the time during which the player familiarized himself/herself with the rules of the game and learned how to control the game's character.

In all of the above mentioned criteria, lower values are better.

In addition, for all possible pairs of criteria, the advantage of one criterion over the other had to be determined. For this purpose, a survey was prepared for people experienced in the video game industry, in which they could assess the importance/advantages of all criteria. In addition, to determine the respondents' experience, the survey included questions about the time spent playing video games in general and which platform games they specifically played.

In order to test the effectiveness of gameplay when using a keyboard and a controller, it was necessary to prepare software that allows for measuring specified parameters. The piece of software has the form of an arcade platform game, measuring the above-defined parameters. The game was created in the Unity engine version 2020.3.2f1. The graphics and the game mechanics have been created to conform to assumptions about platform games. In the game, the parameters enumerated above are measured. When the game is finished, the results are displayed on the final screen.

The LT parameter is measured in seconds as the player learns about character controls and game rules. The GT parameter is also measured in seconds during the game, and timing ends when the player completes the game. The DC and MC parameters are incremented respectively when the player's character dies and when the player presses any button that has not been assigned to character control.

The game has been tested and problems found during testing have been fixed. A screenshot from the game is presented in Fig. 1.

Along with the software, an application form was prepared for people willing to take part in the research. The form contained personal information, such as age and sex, and was used for statistical purposes. Other information was used to organize the tests. In addition, the form contained three questions that helped to assess a person's level of experience with platform games.

Participants in the research were asked to come to prepared rooms at the Lublin University of Technology. A computer with the game installed and two tested control devices were prepared.

Each participant took part in one session of the game in which he/she had to finish the prepared game. Once he/she completed the game the participant was asked to fill out a survey on user satisfaction. In the survey the player assessed his/her experience with the keyboard or controller (depending on which device he/she was using). The time of each game session was limited to 30 minutes.

Fig. 1. Screenshot of the game prepared for the purpose of research

All safety measures related to the prevailing SARS-CoV-2 virus pandemic were taken. The control devices were disinfected after each game session. The participants were required to wear masks covering the mouth and nose at all times. Rooms used were continuously ventilated. Only one room was used at any given time while the other room was thoroughly ventilated.

16 participants signed up for the study. They were divided into two groups of 8 people. People from the first research group used the keyboard while the people from the second group used the controller. The participants' characteristics used for statistical purposes, together with information on whether a given person was considered an experienced player, are presented in table 1.

Table 1. Research groups and participants assigned to them

Groups	Keyboard			Controller		
Participants	Sex	Age	Exp.?	Sex	Age	Exp.?
	M	24	Yes	M	26	Yes
	M	23	Yes	M	24	Yes
	M	23	Yes	M	24	Yes
	M	21	Yes	M	24	Yes
	M	24	No	M	24	No
	F	24	No	M	24	No
	F	24	No	M	24	No
	F	23	No	F	26	No

12 men and 4 women, all 16 aged 21 to 26, participated in this study. Due to the low number of participants caused by the pandemic, they were not divided into additional groups by experience. However, their experience was taken into account in observations presented at the end of the paper.

3. Results

The survey on the importance of studied parameters was addressed to people with experience in the field of video games. It received 57 responses, of which 18 were rejected due to inconsistent answers. Each question had 9 possible answers ranging from 1 to 9, where the number 1 denoted that the first parameter is very important and the second parameter completely unimportant, and 9 denoted the opposite situation. For each pair of assessed parameters, a mean was calculated from respondents' answers. The calculated means needed to be converted into a number corresponding to the importance values for the purpose of the AHP ($\bar{x}_2$) method (that is into a number from the following set {(1/5),(1/4),(1/3),(1/2),1,2,3,4,5}). In order to do that the non-integer part of the mean was left out and the following formula was used:

$$\bar{x}_2 = \begin{cases} \frac{-1}{\bar{x}-6} & ,\bar{x}-4<1 \\ \bar{x}-4 & ,\bar{x}-4\geq 1 \end{cases}$$

where $\bar{x}$ – is the average value of the answers for each of the questions (each pair of parameters). The reciprocal of this number was also calculated. It was needed to fill in the matrix, which was then used to calculate the parameter weights using the AHP method. The means of the responses for each pair of parameters, the transformed values expressing the importance values and their reciprocals are presented in table 2. For each pair of parameters,

the value of $\bar{x}_2$ below 1 means that the left parameter is more important than the right one, and the value above 1 means that the right parameter is more important than the left.

Table 2. Transformed parameter importance survey results – average, importance value, reciprocal

Parameter pairs	LT:DC	LT:MC	LT:GT	DC:MC	DC:GT	MC:GT
$\bar{x}$	4.79	4.26	5.38	4.95	5.23	5.64
$\bar{x}_2$	0.83	0.57	1.38	0.95	1.23	1.64
$\bar{x}_2^{-1}$	1.20	1.75	0.72	1.05	0.81	0.61

The transformed importance values for all pairs of parameters were placed in the matrix presented in the form of a table (table 3).

Table 3. Matrix of parameters with importance values

Parameters	DC	MC	GT	LT
DC	1	1.05	0.81	0.83
MC	0.95	1	0.61	0.57
GT	1.23	1.64	1	1.38
LT	1.20	1.75	0.72	1

After calculating the geometric mean of the rows in the matrix, weights for each parameter were calculated. The weights were used in an analysis of the results of the research with the participants. Geometric means of the rows are shown in table 4. The parameter weights have been rounded to the second decimal place.

Table 4. Geometric mean of the AHP matrix rows, computed priorities and their sums

Parameter	Geometric average	Weight
DC	0.916617412	0.22
MC	0.758109736	0.19
GT	1.291686175	0.32
LT	1.108888674	0.27
Sum	4.075301997	1

To make sure that the weights were correctly calculated, the CR coefficient was also calculated. It defines the logical consistency of the assigned weights. The coefficient value was 0.13. Its value slightly exceeded the typical threshold (0.1), but it was assumed to be sufficiently close (due to the number of received answers).

Then the research with participants described in section 3 was carried out. Results are presented below on the values of the measured parameters and responses to the survey on participants' satisfaction with using a given control device. Table 5 shows the results for the participants using the keyboard and table 6 for participants using the controller.

Table 5. Test results for the group using the keyboard

KEYBOARD									
Parameters				Survey					Exp.?
DC	MC	GT [s]	LT [s]	1	2	3	4	5	
55	0	547	14.28	2	3	2	3	2	Yes
157	23	1269.35	31.49	2	1	1	2	3	Yes
94	1	1163.12	26.49	1	1	1	1	1	No
24	0	396.82	18.08	1	2	1	2	1	Yes
145	17	1678.28	22.26	2	1	2	4	2	No
91	6	997.61	29.99	2	1	1	1	1	Yes
82	15	1098.94	31.03	1	1	2	2	1	No
99	2	1243.62	27.24	1	2	2	2	1	No

Table 6. Test results for the group using the controller

CONTROLLER									
Parameters				Survey					Exp.?
DC	MC	GT [s]	LT [s]	1	2	3	4	5	
107	30	1051.90	13.03	3	3	4	3	3	Yes
384	26	3095.85	30.34	3	3	3	3	2	No
113	10	876.49	17.21	1	3	3	2	2	No
106	2	738.38	13.11	2	2	1	1	1	Yes
105	6	809.57	48.74	2	2	3	2	2	No
239	519	2061.62	30.19	2	3	3	2	2	Yes
82	4	824.93	47.54	3	2	3	2	2	Yes
80	26	1444.44	19.86	7	6	7	5	7	No

4. Results analysis

The results of this research with participants described in Chapter 4 are presented in box graphs (Fig. 2). The graphs show the priority of the keyboard over the controller in the case of DC and MC parameters and the priority of the controller over the keyboard in the case of GT and LT parameters. Due to high variations in the results, a decision was made to use the median instead of the mean of values measured during the tests. Median parameters for both tested devices were determined.

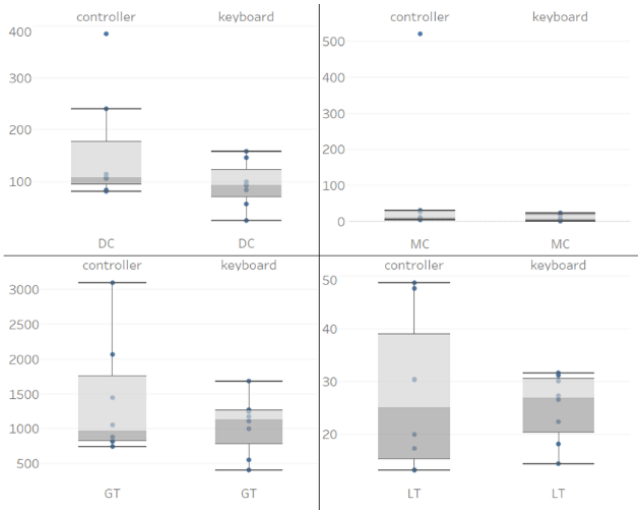

Fig. 2. Box graphs showing the values of all parameters for both tested alternatives (GT and LT are expressed in seconds)

Using the AHP method, two final results were calculated for the tested alternatives. The results are presented in table 7.

Table 7. Test results for both alternatives for median parameter values

	Keyboard	Controller
DC	92.50	106.50
MC	4.00	18.00
GT	1131.03	964.20
LT	26.87	25.03
Result	0.93	0.82

According to the results in table 7, of both compared devices, the keyboard turned out to achieve better results while playing arcade platform games. The parameter values indicate that it was easier to learn to control the character using the controller device, but fewer mistakes were made when using the keyboard.

In addition, the results of the survey regarding the satisfaction of using a given device show that the vast majority of participants using the keyboard assessed their experience with the device as "Very Positive" or "Extremely Positive", and the vast majority of participants using the controller – between "Positive" and "Very Positive". Among the responses of participants using the controller, there was also one very negative answer.

4.1. Additional observations

Without taking into account the variation in test results and calculating the final score for the keyboard and controller using mean values instead of medians, the keyboard had the smallest values for all parameters. This means that the end result for the keyboard was 1 (the highest possible) and the controller's score was 0.65.

Given the low number of participants and the study results, discarding the outliers proved pointless. For each of the alternatives, only four results remained and the final results of the AHP method of the two alternatives were evened out. This happened, however, because in most cases results making the final result lower were rejected for the controller, and results making the final result higher were rejected for the keyboard tests.

When looking at the results of only one group (the participants who were considered experienced or inexperienced), the final results also show the advantage of the keyboard over the controller, in spite of the low number of participants.

In addition, participants using the controller had an opportunity to choose which way of moving the character they wanted to use – the left knob or arrows. During the research, it was noted who used which method. It turned out that half of the participants (4 out of 8) used the knob and the other half used the arrows. This may mean that the ability to choose how to control the character affects the comfort of the player's gameplay.

5. Conclusions

After analyzing the results, it can be concluded that the keyboard is a device more accessible to users when playing arcade platform games. The results of surveys completed by participants at the end of each game session only confirm that using a keyboard is more satisfying than using a controller while playing this type of game.

Research may be repeated in the future with more participants to confirm or negate the above results. In addition, with a higher number of participants, it would be possible to divide participants into additional groups by experience to further investigate differences between control devices.

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A REVIEW OF CURRENTLY USED ISOLATED DC-DC CONVERTERS

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Abstract. *This paper presents a review of the most popular isolated DC-DC converters topologies. Presented solutions are divided to two main groups. First – unidirectional soft switched isolated DC-DC converters and the second one – bidirectional soft switched isolated DC-DC converters. It introduced also a two main DC-DC converters control methods. The collected results of research, simulations and tests of individual solutions carried out with different assumptions allowed for the preparation of a summary. The formulated conclusions can define the direction of development of resonant converters and a specific starting point for further research on control algorithms as well as improving the efficiency of DC converters.*

Keywords: DC-DC power converters, soft switching, electric vehicles chargers, LLC resonant converter

PRZEGLĄD OBECNIE WYKORZYSTYWANYCH IZOLOWANYCH PRZETWORNIC PRĄDU STAŁEGO

Streszczenie. *W artykule przedstawiono przegląd najpopularniejszych topologii izolowanych przetwornic prądu stałego. Zaprezentowane rozwiązania podzielone zostały na dwie główne grupy. Pierwsza – jednokierunkowe izolowane przetwornice prądu stałego pozwalające na osiągnięcie miękkiej komutacji, druga – dwukierunkowe izolowane przetwornice prądu stałego osiągające posiadające możliwość pracy w trybie miękkiego przełączania. Zebrane wyniki badań, symulacji oraz testów poszczególnych rozwiązań przeprowadzanych przy odmiennych założeniach pozwoliły na opracowanie podsumowania. Sformułowane wnioski mogą definiować kierunek rozwoju przetwornic rezonansowych oraz swoisty punkt wyjścia do dalszych badań nad algorytmami sterowania jak i poprawą efektywności przetwornic prądu stałego.*

Słowa kluczowe: przetwornice DC-DC, miękka komutacja, ładowarki pojazdów elektrycznych, przetwornice rezonansowe LLC

Introduction

The number of applications of DC-DC converters in the field of electrical and electronics is constantly increasing. They are used, among others, in small converters found in mobile phone chargers, through computer power supplies, photovoltaic installations, electric vehicles (EV), EV chargers and large energy storage. At present, micro-photovoltaic installations [17, 23], energy storage [27] and electric vehicle chargers [14] process the largest amounts of energy while remaining applications with the most variable load levels [12]. Such characteristics of the converters work require from engineers designing converters to take an un-conventional approach to the subject and to constantly search for the most effective solutions to minimize the burden on the energy system and thus reduce greenhouse gas emissions [29]. The multitude of converters used in electromobility as grid to vehicle (G2V) and vehicle to grid (V2G) chargers, or inside of electrical vehicles forces to continuous research into more efficient DC-DC converters with higher energy density. The article presents an overview of the latest solutions within DC-DC converters [22], focusing on the most effective ones. The focus was on a broader look at the subject of DC converters, showing not only the difference in topologies and their application, but also review of the latest control solutions. The collected results of research, simulations and tests of individual solutions carried out with different assumptions allowed for the preparation of a summary. The formulated conclusions can define the direction of development of resonant converters and a specific starting point for further research on control algorithms as well as improving the efficiency of DC converters.

This article is divided as follows: 1 – Unidirectional soft switching DC-DC converters, 2 – Bidirectional soft switching DC-DC converters, 3 – Comparison between two most popular control method. Section 5 provides a conclusions.

1. Unidirectional soft switched DC-DC converters topologies

Many of the mentioned devices require specific functionality, the most important of which is a galvanic isolation between power source and load terminals [6]. This paper are focused on currently used isolated DC-DC resonant converters solutions.

1.1. LLC series-parallel converters

Most popular DC-DC resonant converters used for one-way energy transfer is designed in series-parallel LLC/LCC topology what is shown in Fig. 1. This kind of solution is a good compromise between efficiency to cost, thanks to not so much complicated design [8].

Specific of this kind full bridge converters and synchronisation of control signals allows to achieve zero voltage switching (ZVS) in turn-on stage and zero current switching (ZCS) in turn-off stage of an opposite pair transistor when converter is working on resonant frequency [15]. Difficulties in maintaining resonance at low load mean that it should be designed to operate at medium and high % of maximum power. This disadvantages causes that LLC/LCC topology is a good and efficient option only, when load is easy to predictable and constant at the most of time or work time on low load is occasional [1, 4, 20, 38].

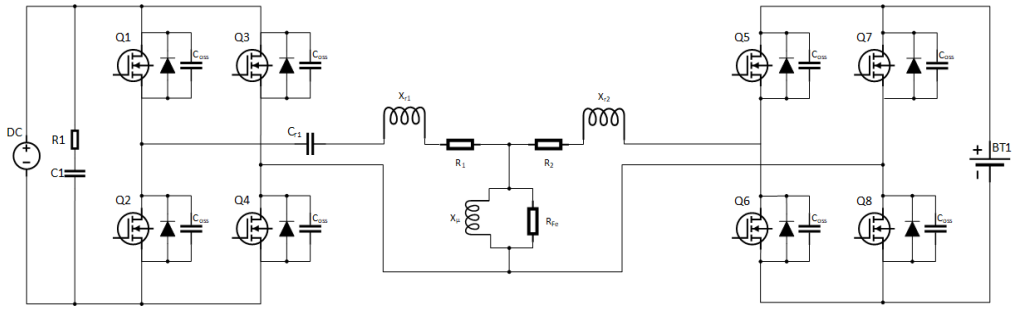

Fig. 1. Dual Active Bridge LLC resonant converter simplified topology

1.2. Multi output LLC converter

Every of battery electric vehicle (BEV), plug in electric vehicle (PEV) and fuel cell electric vehicle (FCEV) needs to be useful minimum a few power converters inside [8, 13].

In typical EV, one of power converters is needed to transfer power between high voltage (HV) battery and engine(s) inverter(s) [7, 11], second between HV battery and wall charger, third one between HV line to low voltage (LV) line for charging a LV battery – usually 12 V or 24 V in truck and buses which is needed to supply onboard LV devices as lights or audio system and the last one – DC/AC inverter to supply high voltage air conditioner (HVAC) [7]. As was shown on Fig. 2 in FCEV is another one of converter- working in step-up mode- to boost voltage from fuel cell which is typically at low value – for example 165 V in 45 kW fuel cell generator designed for buses [43]. Many converters in one vehicle, working on different voltages and power levels increasing weight, cost and total mass of entire vehicle. A partial solution to this problem has been proposed in [10] and named as multi output LLC converter.

Proposed converter topology is based on a basic LLC converter but with modified transformer, simplified structure is shown on Fig. 3. In multi output converter topology, transformer has been exchanged to multiple winding transformer. Properly designed of each part of converter allows to reach a soft switching similar to typically LLC topology [34] but with reducing time when converter is working unstable – on very low load. That allows to integrate two or more DC-DC isolated converters to one device with different voltage outputs.

Integrated solutions reduce total net mass of the vehicle, and takes up less space that can be devoted to increasing the usable space.

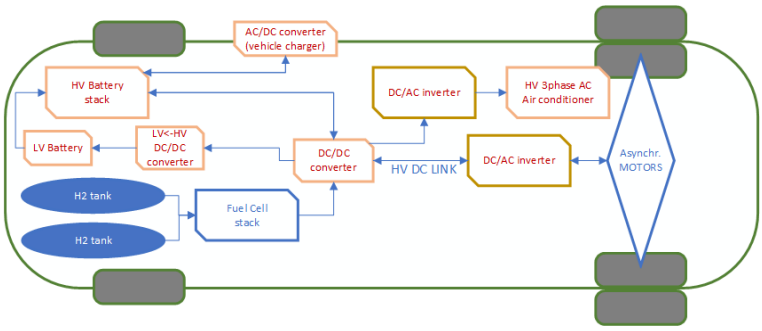

Fig. 2. Main power converters in Fuel Cell Buses and energy flow directions

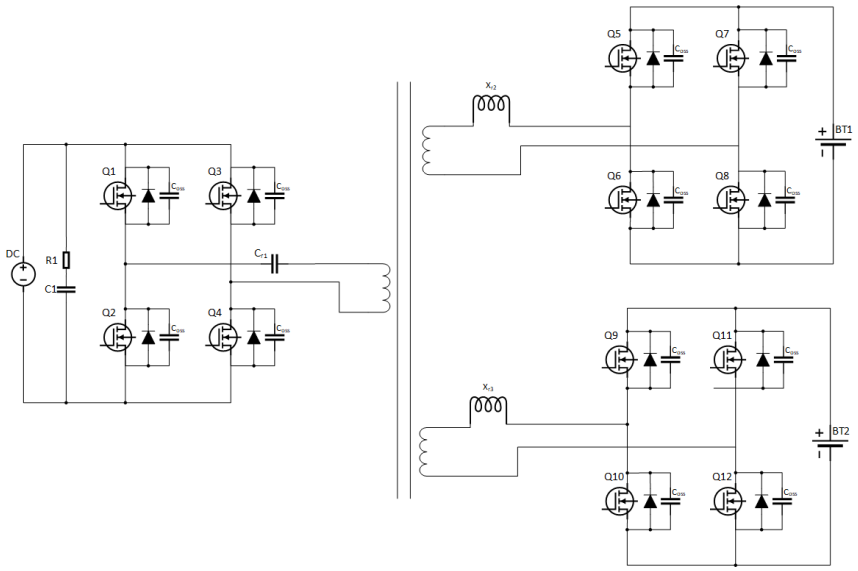

Fig. 3. Multi output Dual Active Bridge LLC (unidirectional soft switched) converter simplified topology

2. Bidirectional DC-DC converters topologies

Bidirectionality – next to efficiency and isolation – one of the most important functionality required on electromobility power converters market. Due to the continuous increase in the number of all kinds of EVs, from scooter, EVs, light commercial electrical vehicles (LCEVs), FCEVs to trucks and FC trains, energy system is getting more and more unstable. To limit this process it is necessary to provide a new services, one of them is bidirectional energy transfer between grid and users. Traditional system is working in one way, customers uses energy from grid and that`s all, but now it's not enough.

For several years, research has been carried out on the possibilities and improvements of bidirectional energy transfer through isolated DC-DC converters. One of the proposed solutions is G2V-V2G service, the main assumption is sharing energy stored in EVs with the grid in hours when it is not needed for EVs customer, for example when owners are in work. Then the grid operator could use EV batteries as huge energy stores, provided that they are charged before the designated time (e.g. end of EV owners' working hours). Thanks to V2G services, the network receives decentralized energy storage at predictable hours and capacities without incurring the cost of their purchase. On the other hand, the customers get the opportunity to purchase energy at reduced costs. Second perspective to using bidirectional transfer by EVs owners or road assistance services is Vehicle to Vehicle (V2V) energy transfer. To clarify in most popular vehicles – with internal combustion engines- when they run out of fuel then it is possible to call on road assistance or friend who can deliver fuel in a canister. In EVs, such problems can happen even more often than in internal combustion cars- long route, frost or sweltering heat, traffic jam and running out of battery energy reserves. These are also the assumptions of the services like V2V energy transfer. Inside V2V service is a special devices based on bidirectional isolated DC-DC converter and charging regulator which allows to transfer energy directly between vehicles.

A mentioned problems are a two main reasons why bidirectional energy transfer possibilities are so important.

2.1. CLLC dual bridge- series-parallel converters

The disadvantages of LLC topology and the requirements from electromobility market as a high efficient bidirectional energy transfer possibilities led to creating a dual active bridge [19] (DAB) CLLC converters. [2, 9, 11, 28].

Main difference between LLC and CLLC [36] topology is an expansion of resonant tank up to four or more elements involved to resonance what is shown on Fig. 4. In the V2G direction, the magnetizing inductance is not used in resonance, leaving typical series LC resonance [9, 31]. That system simplification causes losing a soft switching and decreasing a gain under 1, thus limiting the possibilities of adjusting the output voltage. Thanks to extended resonant tank now it is possible to achieve work in resonance frequencies in both, grid to vehicle (G2V) [25, 26], and vehicle to grid (V2G) way of energy transfer. Similarly to LLC converters- working near resonance frequencies, it enables soft switching in ZVS/ZCS mode [28], which significantly reduces switching losses and improve the performance of the entire device [3, 8, 9]. Described more deeply in [2, 3, 8, 9] advantages of CLLC DAB isolated DC-DC converters proves superiority of this topology than LLC converters in systems where bidirectional transfer is required.

2.2. Multi module resonant converters

Similar to multi output [18, 33] LLC resonant converter topology, but instead of providing different voltage levels for loads from single source – this kind of converter is designed to allow to supply DC link from different sources [16, 30]

Another bidirectional isolated DC-DC converter is presented at [12]. Presented topology is a combined system of a single source, and multi full active bridges (FAB) or multi half active bridges (HAB) on secondary side delivering power to single load. Dividing total load to multi FABs while maintaining soft switching allows to switching on higher frequencies without increase power loses [5].

In [16] multi input FABs converter is presented, that kind of topology will be used to supply DC link – load by different voltage sources, each of them have their own transformer winding tap. Presented in Fig. 5 combined mode allows to connect via converter for example HV battery on 400VDC, fuel cell stack with 200 V from primary side to load (engines inverters [41] connected to DC link) 500 V, or to receiving energy from engine recuperation breaking to HV batteries, disconnecting fuel cell module maintaining of soft switching mode.

Multi module isolated DC-DC converters that achieve soft switching modes like ZVS and ZCS, could be a optimal solutions for most of EVs and FCEVs which allow to simplified a vehicle cooling system and HV/LV harnesses or power line system.

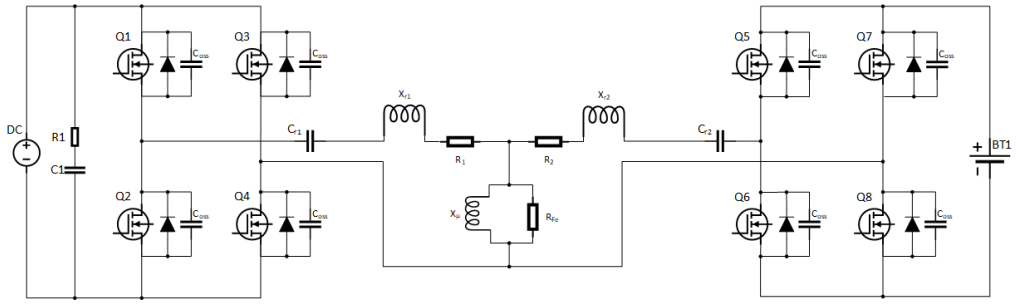

Fig. 4. DAB CLLC (bidirectional soft switched) resonant converter simplified topology

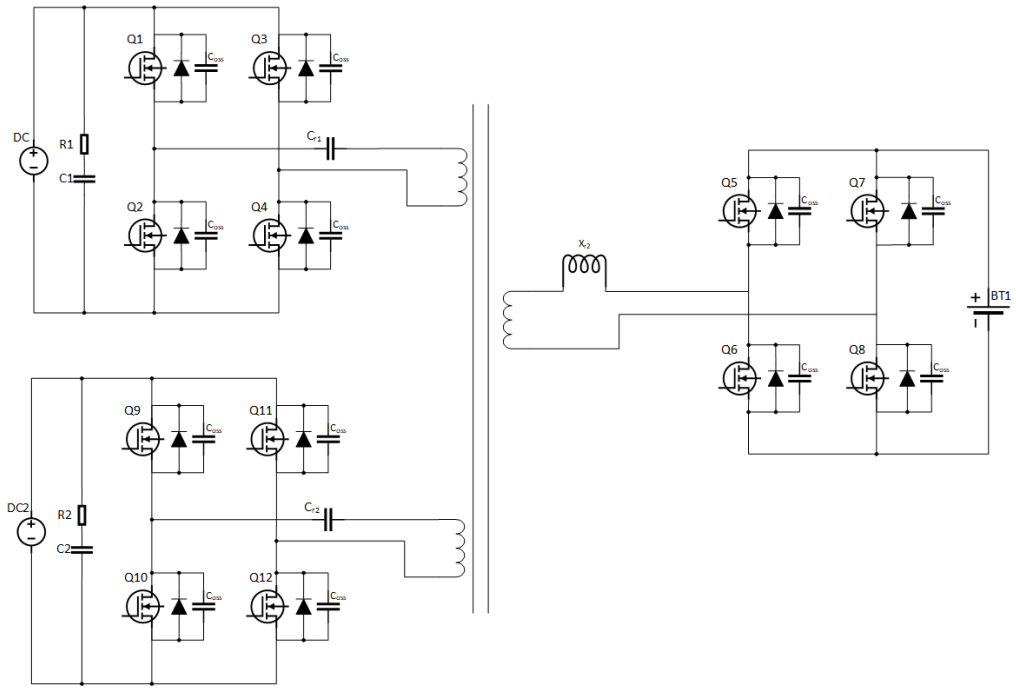

Fig. 5. Multi source DAB (bidirectional soft switched) DC-DC converter simplified topology

3. Frequencies vs phase shifted control method differences

The multitude of isolated DC-DC converters topologies, and pursuit of the highest efficiency resulted in development of few control methods. First from two of the most popular is control by changing frequency, using resonant algorithm. In this type of control method, time phase is fixed at 0° and power is regulated by changing frequency that means – converter is working at resonance point, below or under resonance freq. To achieve a ZVS it is necessary to work near below, at point or above resonant frequency. Second is control via changing phase shift angle to regulate the output voltage [21, 35]. Comparison of the advantages and disadvantages are listed in the table 1.

Table 1. Comparison of disadvantages and advantages between frequency and phase shifted control method [8, 21, 24, 35, 37, 39, 40]

Parameter	Phase shifted control method for DAB converter (PSFB)	Frequency control method for DAB converter
Efficiency for max. load lower than 15%	Higher than freq.	Low, instable below 10% of max. load
Efficiency for max. load higher than 15%	Lower than freq.	Higher than PSFB
Soft switching	ZVS	ZVS and ZCS
Frequency	Constant	Flexible
Power destiny	Lower per 1 kW	Higher per 1 kW
Bidirectional transfer	Possible but complicated	Possible and easiest than PSFB
EMI	Higher than freq.	Lower, signal close to sinus
Synchronisation	Easiest than freq.	Complicated

Phase shifting control is a method which is realized by changing phase between first and second half of H-bridges. This type also allows to use full bridge DABs (FBDAB) topology for synchronous rectifying. If resonant tank are designing like fully symmetrical it is possible to achieve bidirectional fully synchronous isolated DC-DC transfer by changing steering role between H-bridge on the primary with H-bridge on the secondary side of transformer [14]. Control algorithm which is based on PSFB control method is called peak current mode control (PCMC), this is the one of the fastest control method.

Presented review of control method features are more deeply described in [2, 14, 21, 32, 35]. Issues like low efficiency or instable work in load lower than 10% of maximum designed or large switching frequency operating range to satisfy voltage gain requirements causes that frequency control method is a good solution if load parameters are predictable and stable. Otherwise despite lower efficiency at high load, phase shifted control method allows to work in constant frequency and easy way to synchronise DABs in full range of load.

4. Conclusions/summary

The collected results of research, simulations and tests of individual solutions carried out with different assumptions allowed for the preparation of a summary. A multitude of applications where DC-DC power converters can be use shows that is every day and future-proof technology. Series-parallel resonant converters LLC-type is an optimal solutions to transfer energy via isolated converter if power level is predictable and repeatable, and also bidirectional transfer is not required, for example in phone or notebooks chargers. In bidirectional applications it should be applying CLLC DABs resonant or symmetrical DABs topologies with PSFB or frequency changing control method. Designing multi source multi active bridge converters with soft switching allows to supply one DC link from different sources with different voltage levels.

Combination of multi active bridge multi input or multi output converters are one of the possible directions to simplify electric vehicles power lines. Simplification of EVs harnesses allows to designing and routing it on the best way and insulation in conjunction with electromagnetic compatibility requirements of vehicles approval. Another advantage is possibility to design more compact solution in one case (one module) with combined cooling interface. Common heat dissipation system can reducing weight of system integration in the vehicle- not each converter connected with separated valves and steel pipes but one valve on input and one on the output of multi DC-DC converter cooling port. All possible ideas to reduce curb weight are desirable because they affect to available maximum range.

Deeply focusing on details of topologies and control methods must be the starting point to designing more efficient, better matched for application power converters.

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