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Processing and Interpretation of Plethysmographycal Records for Embedded System

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BIOGRAPHICAL NOTES

Ing. Marek Penhaker, PhD. finished MSci in 1996 at Faculty of Electrical Engineering and Computer science in specialization Measurement and Control in Biomedicine at VŠB - Technical University of Ostrava, Czech Republic. He followed his Ph.D. studies with the thesis entitled "The development of the process for systematic diagnostics of vascular system conditions with the use of plethysmographycal record" where he was specialized in biosignal processing and measurement. He received Ph.D. in Technical Cybernetics from VŠB - TU Ostrava. In October 2000 he started working as a professor assistant at VŠB - TU Ostrava in the field of biosignal measurement, transmission and processing. Since 2002 he is Guarantee of MSci specialization Measurement and Control in Biomedicine, from 2003 he is vice-director for research and science of Department Measurement and Control. Currently he is from 2004 Ph.D. tutor specialist for branch Technical Cybernetics. Through his career he published more than 100 original research articles including over 30 peer reviewed journal papers. He is author and coauthor of more than ten books. He received several awards, among them the Siemens in Study of Drive Gear at Mobille Mount with Fuel Cell. His current research interests are focused on sensing, data processing algorithms, instruments for diagnosis and therapy of health corresponding with telemedicine and personal health care.

prof. Ing. Vilem Srovnal, CSc. he teaches at the Technical University of Ostrava since 1966. From 1972 to 1989 he worked as a researcher outside the University of Ostrava. His professional focus is directed into the areas of automatic control theory, embedded and distributed systems management, technology management systems, process control computer and mathematical modeling and simulation A. Associate professor of Technical Cybernetics was appointed in 1990 and for the field measurement and control Technology has been appointed as the inaugural work in 1999. He was appointed Professor of Technical Cybernetics in 2004. Currently, he teaches courses Fundamentals of Cybernetics, analysis of regulatory systems, regulatory systems, operating systems and management Design and implementation of controllers is a member of the International Technical Committee of the TC 4.1 components and technologies for the management of IFAC (International Federation of Automatic Control), also a member of the Czech Committee CNC IMEKO (International Measurement Confederation)

KEY WORDS
Signal Processing, Plethysmography, Wavelet Transform, Expert System, Embedded System

ABSTRACT
The aim of this work was signal processing and interpretation of plethysmographycal records for embedded system. The goal was study of present and advanced methods for records classification by means of mathematical methods, which can be implemented as a part of the embedded medical diagnostics instruments. The diagnosis suggestion was realized by experimental expert system tested on group of patients. Designed embedded system provides plethysmographycal records processing in real time while ensuring the safety and security of these data in a network of biomedical systems.

INTRODUCTION
The finger plethysmography is a noninvasive method for recording pulse waves from fingertips of human extremities. Pulse wave is created by the heart activity and by penetration of blood through the vascular system. Plethysmographycal record is creating by the succession of the pulse wave. Finger plethysmography is fundamental additional investigation of vessels for determination damages of vessels due by the exposition of vibration. The waveform depends on the quality of elasticity of arterial walls. The pulse wave consists from two parts: anacrotic-ascendant, catacrotic-descendant. On the descendant part appears so-called dicrotic notch (or wave) and it gives a very important information about the elasticity of the vascular wall [1].

THE CRITERIONS FOR PULSE WAVE EVALUATION
The record was until now printed on an uncalibrated paper by the implementation printer in the instruments. Evaluation of pulse waves was done by a skilled physician visually or with the help of the most used criterions. Some of that criterion did not take in question the possibility of a change of pulse frequency during examination and from it arose an error in reading of parameters of pulse wave. The error was bigger with more quick pulse frequency.
During the evaluation of the dicrotic wave is important not only the form of the wave but also its location on the katacrotic part of the pulse wave. In time domain is important to observe the location of dicrotic wave on the katacrotic part to the peak of the pulse wave itself because it predicates a lot of about the condition of blood vessels and their elasticity.
In time domain it is very important to find the placement of dicrotic wave on the descendent part of the pulse wave. The advantageous is to use criterion which express the ratios of individual parameters of the pulse wave. We used such parameters, which could better define relations between single parts of pulse wave and limit the influence of the change of pulse frequency and magnitude of amplitude.
Magnitudes ratios of single parts of a pulse wave

$$MVV = \frac{X}{Y} \tag{1}$$

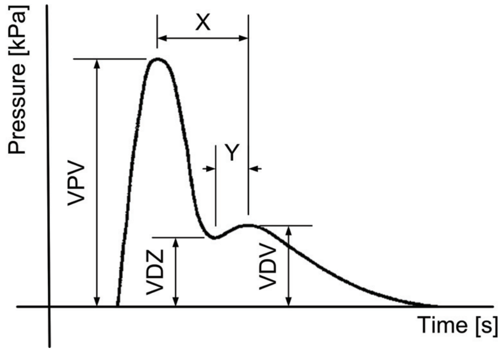

Fig. 1 *Advantage parameters in time domain*

could easier determine, the location placement of particular parts of a pulse wave with respect for the magnitude of pulse wave which could be at every single measurement variable. (1)
Ratios of magnitudes of single parts of a pulse wave could easier determine the location placement of particular parts of a pulse wave with respect for the magnitude of pulse wave, which could be at every

$$V/VDV = \frac{VPV}{VDV},\ V/DZ = \frac{VPV}{VDZ},\ VDV/DZ = \frac{VDV}{VDZ} \tag{2}$$

single measurement variable. These parameters are ratios of magnitude of pulse wave and dicrotic wave (V/VDV) and pulse wave and dicrotic notch (V/DZ), dicrotic wave and dicrotic notch (VDV/DZ). (2)
At present, it is necessary to design the processing of biomedical data so as to permit the realization of this processing via embedded systems, which could involve a network of devices used in health care. It is also necessary to design such a data transmission even in a wireless network, which would ensure secure transmission of data without the possibility of

disruption or hooking of these data.

SPECTRAL ANALYSIS WITH DETERMINATION OF SIGNIFICANT CHARACTERS

The maximum attention is paid now to this domain because it enables to find out the origin of rise of pulse wave in total sum of harmonic frequency which arises during the passage through vascular bed. The final form of the pulse wave is influenced by the sum of progressed and reflected wave.

Very good tool for evaluation of a pulse wave is the analysis by the different mathematical method. The advantage of this evaluation is looking on the pulse wave in whole not only on its parts. It is possible to think about for example distributing of the registered wave with the help of good chosen time base or its mathematical transformation by the operation proceeding as for example Laplace or Fourier transform. The most effective method today is Fourier transform but during the systematic research of elastic reactions of arteries with the help of analysis problems arose because still we do not have systematically methodical unified research of these reactions of the arterial system to various stimulus on the external physical effects on short term changes of blood pressure and other similar stimulus. To this time also was not compiling a question about such analytical interpretation of findings on pathological changed arteries. [7], [8]

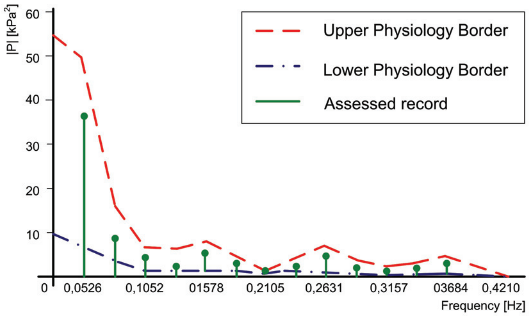

Fig. 2 *Amplitude spectrum of pulse wave displayed with physiological ranges*

This analysis is not good for use for all kinds of periodical functions with them we could meet in human body. For some of them we need too big amount of harmonic elements to be able to get accurate approximation. In this category are signals o ECG, EMG, EEG and other functions. In the opposite side this analysis is suitable for analysis of pulse waves because it is a reaction of the elastic arterial system which alone has a tendency to react by the sinusoidal oscillation (harmonic movement). [4]

In this area the evaluation is orientated more on comparison of records obtained from more measurements done on a lot of patients of the same category of findings and evaluated record it means on particular harmonic components than on evaluation of frequency spectrum of the waveform alone. (Fig. 2) Here is of course important not to separate the analysis in time and frequency domain but to try to find the connection between them. For example at various grades of occlusion or lost of elasticity of vessels in spectrum it is exhibited as a change of magnitude of amplitudes on different frequencies. At first we must classify records to the class spectrums which will characterize damages of vascular system. [5]

THE USE OF WAVELET TRANSFORM TO THE COMPRESS OF DATA

Today is usual to use very often wavelet transform (WT) which serve for before all to time frequency analysis of data and generalization of filtration. It provides also some further possibilities such as compression of data with the little lost of the information value. Because we need to store patient's records from every measurement for long time the problem with the data saving arises because the data capacity is very big. [2]

The important characteristic of wavelet is intellectual simplicity familiar to the used Fourier accesses and also very important computer effective. Easy and quickly is possible to transform with the help of discrete wavelet transform (DWT) big files of data which is an opposite to the classical discrete Fourier transform (DFT).

DWT in the same way as DFT is obtained by suitable discretization from the pertinent integral transformations. If the FFT has a complicated calculation in rules O(n log2 n), than in the DVT it is often a decrease as far as to O(n) it means that it is even faster. [3]

For verifying of proceedings at application WT was programmed our testing toolbox in the program MATLAB and we used it for performing necessary calculations. The transformation was applicated on a signal of pulse wave with the characteristic vector with the 512 points length. Wavelet transform was applicated on the signals with base:

- *Daubechies : D2, D4, D8*
- *Haar : H1, H4*
- *Walsh - Paleye : W-P2, W-P4*

A lot of wavelets bases exist which we can use for transform but for correct analysis are necessary bases to be orthonormal what these bases fulfilled.
WT does decomposition on signal components. The result of the transformation is a signal with the length one half of original signal and also cofactor is the same length.
The cofactor includes complementary information about a signal. Results of compression and decompression of particular signals are shown in (5) and the compression was done on the one quarter of original length. In the table are these parameters: remained energy (r.e.), maximum error (m.e.) and standard deviation (σ).
From the (5) we can find out that when we use the Daubechies (D) transformation base the partial deformation of the signal appears after the reverse decompression before all at the grade 2 what is caused by this that coefficients are tabulated as approximate values. At the compression and decompression was the transformation matrix corrected in such way to suppress the periodicity of signal as it is shown in the first two lines in the table. In the third and fourth line was matrix corrected not to be the periodicity of signal suppressed.
Results of decompression with the use Walsch-Paley and Haar's base are the same as at the base H1 - remained energy = 100%, maximum error and standard deviation is in the rule e-33 this error is caused by around numbers during the calculation on the computer. If we execute transformation of signal PV with the use of D base we obtain the signal its course is nearly the same as the signal before the transformation, what we can verify by comparison of both signals.
Wawelet transforms the signal with the use of windows or wavelet function. The main advantage of WT is its ability to analyze the signal with variable time frequency resolution. WT enables to analyze of the signals with multiple resolution that is done by application gradually expanded window´s function. For the analyze of high frequencies the narrow time window is used for analyze of low frequencies the time window broad. The signal is during this transform divided to the set of certain functions (wavelets).
The basic function of transformation is so called maternal wavelet. The next functions are derivated from the maternal wavelet with gradually widening and shifting in time. The original signal could be reconstructed by the inverse transformation. The joint WT is defined (3) a (4).

$$WT(\tau, l) = \int_{-\infty}^{+\infty} x(t)\,\psi_{\tau,l}(t)\,dt \tag{3}$$

$$\psi_{\tau,l}(t) = \frac{1}{\sqrt{l}}\,\psi\left(\frac{t-\tau}{l}\right) \tag{4}$$

where:

τ time shift of wavelet windows function (dilatation)

l scale that could be recount to frequency

$\psi_{\tau,l}(t)$ wavelet function

ψ transform function (basic - maternal wavelet)

x(t) analyzed signal (signal)

The maternal wavelet ψ is the prototype for creation of the other windows function $\psi_{\tau,l}$,l(t). Wavele that are created from maternal wavelet have the different scale 1 and different position τ(shift), but the identical form. Constant l-1/2 presents the normalization of energy.
If we install relation (4) into relation (3), we get the direct transcription for joint wavelet transform that represents the correlation between the input signal x(t) and function wavelet ψ.

$$WT(\tau, l) = \frac{1}{\sqrt{|l|}} \int_{-\infty}^{+\infty} x(t)\,\psi\left(\frac{t-\tau}{l}\right)dt \tag{5}$$

pulse wave	D2			D4			H1		
	r.e.	m.e.	σ	r.e.	m.e.	σ	r.e.	m.e	σ
original normalized original with periodicity normalized with periodicit	99,88	0,284	0,0	99,47	0,507	0,0	100	0,0	0,0
	99,97	0,16	0,0	99,8	0,39	0,0	100	e-16	e-33
	99,95	0,16	0,0	99,99	0,07	e-7	100	e-16	e-33
	99,99	0,96	0,0	99,99	0,028	e-06	100	e-16	e-33

Tab. 1 *Results of compression and decompression of particular signals*

During the evaluation of signal compression it is not possible to check the quality only according the numeric values of particular parameters but it is also very important to evaluate it by eye view of an expert. Such evaluation is also very important at all medical records.

It is evident that results for Daubechies bases grade 2 give the best numeric results during the processing of the pulse wave. From it appears the applicability of its use for further processing. Even the expert verified this fact. [5]

The PV compressed on the one quarter of original signal has the same spectrum and we save remarkable part of capacity for storage of data files and time necessary for calculation FFT. If we want to save the original signal unchangeable we need after the transformation save the information in cofactor too. Even here we need to save disk space for data storage by the suitable zero setting (filtration) of cofactors. At the filtration we put zero setting on some values of cofactors and for reverse transformation-decompression only dominant values. More methods for zero setting exist: quantile, hard, soft etc.

Table 2 is shown labeling of the chosen base o transform (D2,HI), type and magnitude of zero setting, remained energy after zero setting and decompression (r.e.),maximum total error of decompressed signal, standard deviation (σ).

From the Tab. 2 we can see that when we choose the suitable base for example D2 we can at quantile tresholding 100 % value of cofactors and reverse decompression remain 99,86 % of energy. For saving of signal is enough to save from the original 512 values only 128 (compressed signal) plus 0 (cofactor); it is together only 128 values.

From the introduced results is visible that the most appropriate is Daubechies base. We can make a conclusion that it is possible to use for analysis of the spectrum compressed data and to save the time which we need for decompression.

tresholding	%	D2		D4		H1	
		r.e.	m.e.	r.e.	m.e.	r.e.	m.e.
quantile	80	99,87	0,28	99,47	0,5	99,97	0,017
	100	99,86	0,28	99,44	0,5	99,83	0,074
hard	80	99,87	0,28	99,46	0,5	99,95	0,029
	100	99,87	0,28	99,46	0,5	99,92	0,035

Tab. 2 *Results of filtration quality by the use different methods*

EVALUATING BY EXPERIMENTAL EXPERT SYSTEM

The expert system creates the entire elaboration of plethysmographycal records and it is able to simulate the work of doctors at the determination of diagnosis.

In the final summary the evaluation by the expert system will include the evaluation in time domain with the help of existing [1] and supplementary criterions and it will contain the evaluation of parameters obtained during the evaluation in frequency domain. [9]

The experimental testing of proposed expert system for support of diagnoses on the basis of analysis of plethysmographycal record was realized by problem orientation of fuzzy rule based interactive expert system LMPS v 32.0 (Linguistic Model Processing System) [6] [7].

The problem orientation of fuzzy model system LMPS is done on the basis of expert evaluation of the real data measured by analyses of real plethysmographycal records and supplemented with diagnosis declared by doctor. In the present the system is able to recognize two chosen diagnoses II and I.

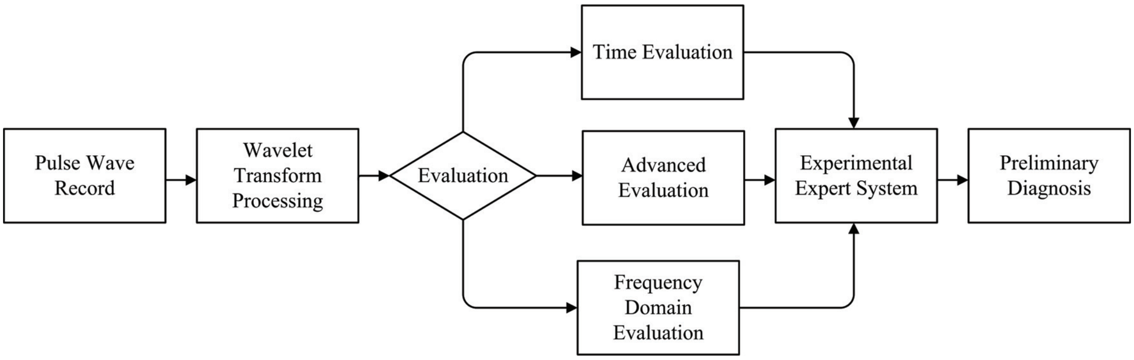

Fig. 3 *Model of processing and interpretation method*

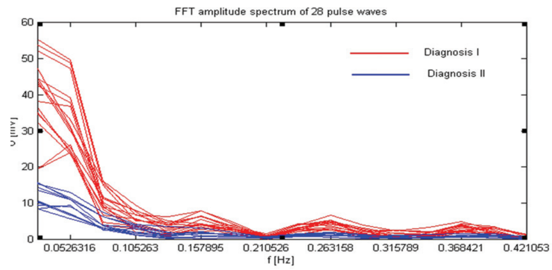

Fig. 4 *Amplitude and frequency spectrum of 28 pulse wave records*

The set of 28 measurements was used for testing method (Fig. 3). Experimental verification of diagnostic effect of suggested method for evaluation of plethysmografycal records was done on four real records (Fig. 4, 5). These test records serve for verification of predicative abilities of suggested bases and for verification of estimation accuracy of diagnostic effect. [10]

record number	Base A y		Base B y		Base C y		diagnosis of physician
	I	II	I	II	I	II	
1	0,82	0,12	0,92	0,08	1	0	I
2	1	0,35	0,69	0,31	1	0,5	I
3	0	1	0	1	0	0,9	II
4	0,38	1	0,09	0,64	0,17	0,83	II

Tab. 3 *Rate of possibilities of expert system outputs for particular bases*

The expert system proved in use good results (Tab. 3). The size of patient's set influenced the number of output diagnoses. Not all-possible diagnoses were found because they were not at this set of patients present.

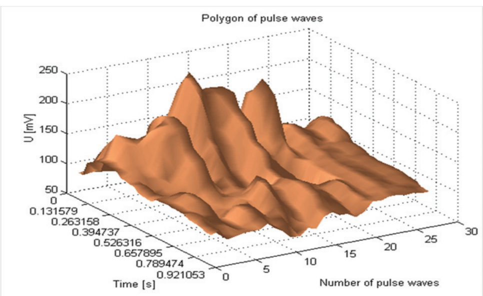

Fig. 5 Time course of 28 records of pulse waves

DESIGN RULES OF PLETHYSMOGRAFYCAL EMBEDDED SYSTEM

Embedded software processing is different from the conventional software processing, for these reasons, the limited size of embedded systems memory or their performance. Other restrictions may be the availability, robustness and energy consumption. Plethysmographycal signal processing has to modify to accept performance of the embedded system processor when we want use it for health home car system. For this application is also important design of the communication system in the wireless embedded systems net. Choosing processor performance has to ensure security data coding by cryptographic methods, which ensures secure data transfer so that he could not get to unauthorized person.

CONCLUSIONS

The aim to make the evaluation of plethysmographycal records more accurate leads to an idea to create the systemic procedure for evaluation of pulse wave. In order to filtration and storage of modified signal was taken an advantage of possibilities of the new mathematical means of wavelet transform and the final conclusion was made by expert system.
This method was already successfully proved on the small tested group of people. But we need to perform more explorations on much bigger set of patients to find out the answer to the question if this method is really effective for elaboration of correct diagnosis, monitoring of a development of diseases of the vascular system and effect of the treatment.
Thereafter it will be done the final appraisal of this method. Only the further research will declare if it is possible to use this transform more often for analysis of a plethysmographycal record. But even the negative conclusion could have an informative value. In next research we would design also plethysmographycal apparatus as the embedded system for home car system.

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cal engineering systems VI".

REFERENCES

[1] I. Oliva, K. Roztočil: Pulsová vlna v diagnostice ischemické choroby dolních končetin, Aviceum, 1982

[2] G. String, T. Nguen: Wavelets and filter banks, Wellesley - Cambridge press, USA 1996

[3] I. Oliva, J. Ipser, K.: Kotlikova, Evaluation of pulse wave morphology by Fourier´s harmonic analysis, Physiol. Bohemoslov. 5, 1986, s. 81 - 87

[4] M. Pokorny: Umělá inteligence v modelování a řízení, BEN Praha, 1996

[5] Krejcar, O., Janckulik, D., Motalova, L., "Complex Biomedical System with Mobile Clients". In The World Congress on Medical Physics and Biomedical Engineering 2009, WC 2009, September 07-12, 2009 Munich, Germany. IFMBE Proceedings, Vol. 25/5. O. Dössel, W. C. Schlegel, (Eds.). Springer, Heidelberg. (2009)

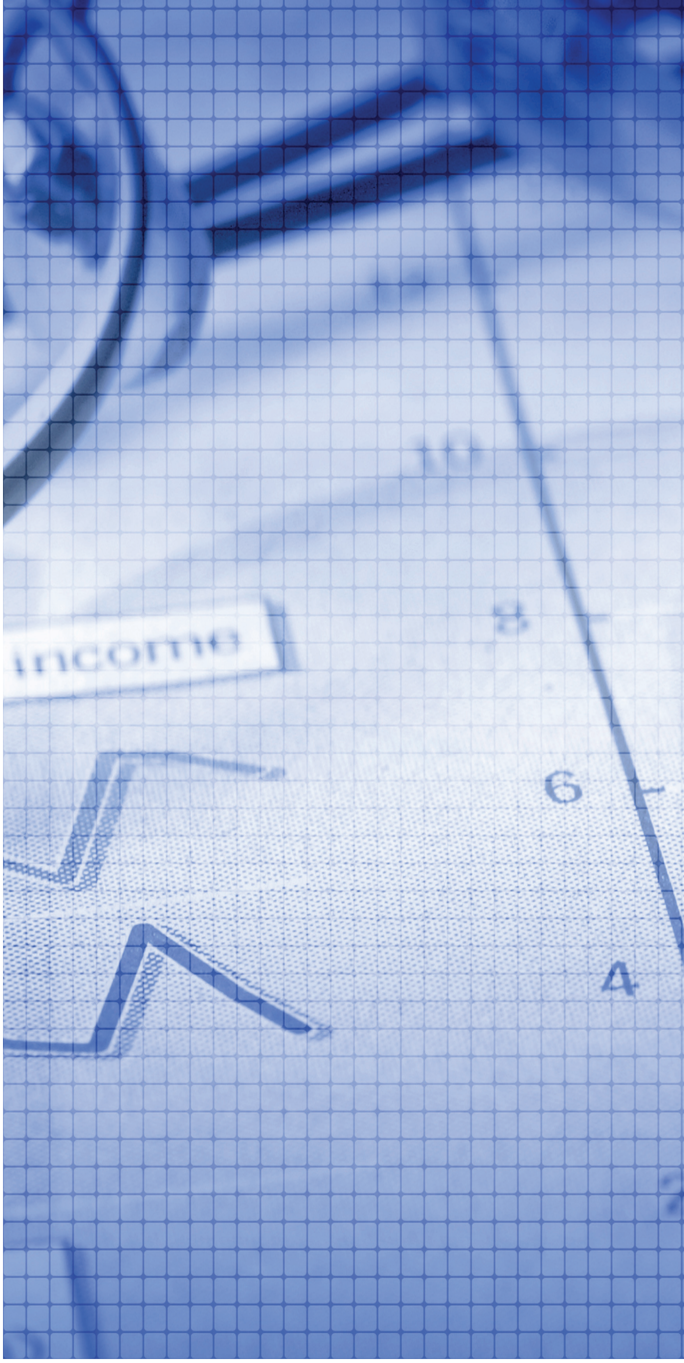
[6] M. Penhaker , M. Cerny, M. Rosulek "Sensitivity Analysis and Application of Transducers " 5th International Summer School and Symposium on Medical Devices and Biosensors, JUN 01-03, 2008 Hong Kong, PEOPLES R CHINA, Pages: 85-88 Published: 2008, ISBN: 978-1-4244-2252

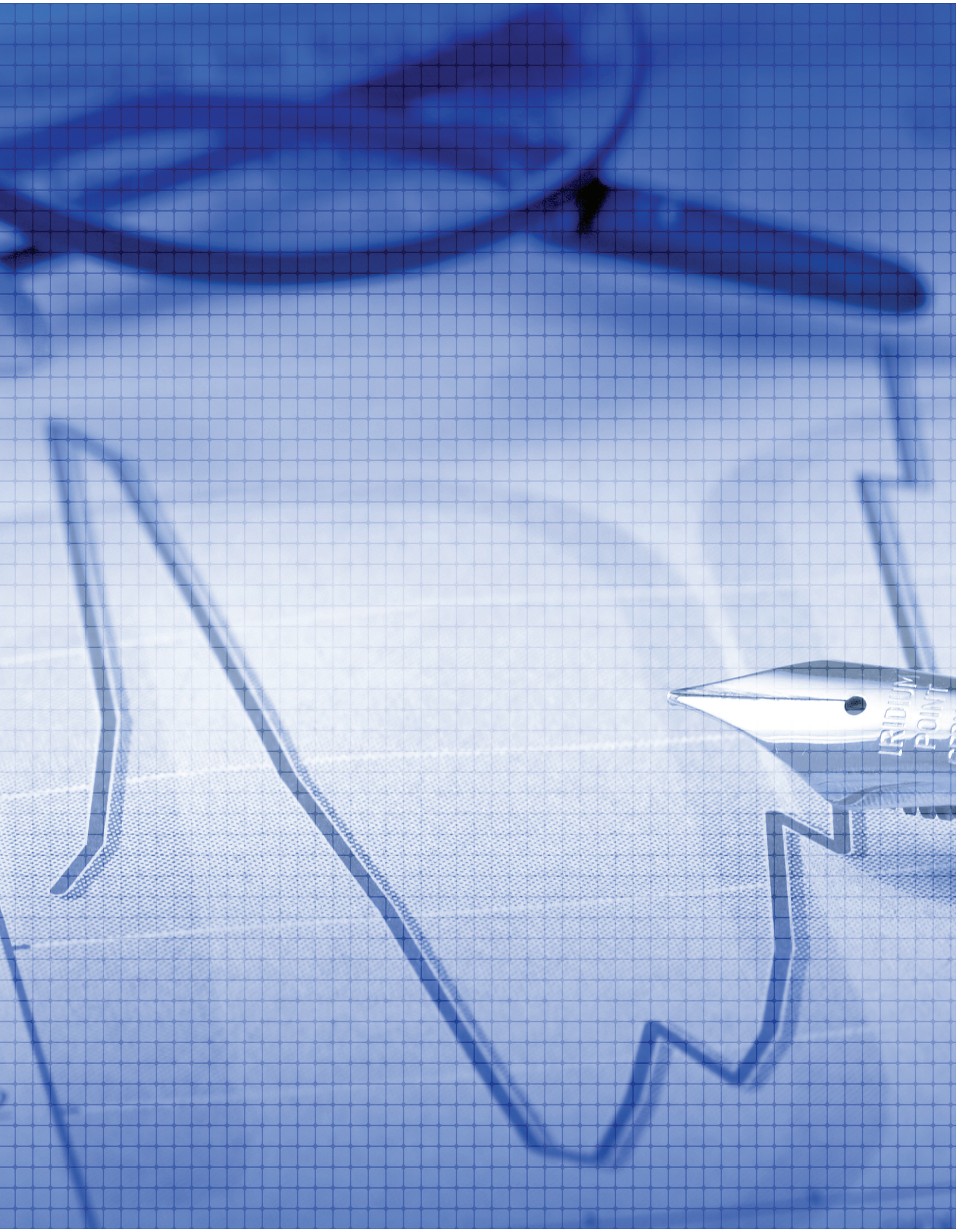
[7] V. Kasik, "FPGA based security system with remote control functions." 5th IFAC Workshop on Programmable Devices and Systems, NOV 22-23, 2001 GLIWICE, POLAND, IFAC WORKSHOP SERIES Pages: 277-280, 2002, ISBN: 0-08-044081-9

[8] Zurek, P., Krejcar, O., Penhaker, M., Cerny, M., Frischer, R. Continuous Noninvasive Blood Pressure Measurement by Near Infra Red CCD Camera and Pulse Transmit Time Systems In Proceedings of 2010 Second International Conference on Computer Engineering and Applications ICCEA 2010, 19. – 21. March 2010, Bali Island, Indonesia, Volume 2NJ. IEEE Conference Publishing Services, 2010 p. ISBN 978-0-7695-3982-9

[9] Penhaker, M., Augustynek, M. Finger Plethysmography Classification by Orthogonal Transformatios Electrical Parameters. In 2010 The 2nd International Conference on Telecom Technology and Applications, ICTTA 2010. March 19-21, 2010, Bali Island, Indonesia. 2010, p. 173–177. ISBN 978-0-7695-3982-9

[10] M. Penhaker, M. Cerny, L. Martinak, et al. HomeCare "Smart embedded biotelemetry system" Book Series IFMBE proceedings World Congress on Medical Physics and Biomedical Engineering, AUG 27-SEP 01, 2006 Seoul, SOUTH KOREA, Volume: 14, Pages: 711-714, 2007, ISSN: 1680-0737, ISBN: 978-3-540-36839-7

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