HISTORY AND BIOMEDICAL APPLICATIONS OF DIGITAL SIGNAL AND IMAGE PROCESSING

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ABSTRACT

The paper presents in its initial part historical notes to the development of digital signal and image processing methods. The following case studies are devoted to their application in biomedicine and they include the use of computational intelligence in EEG and EMG signal processing, image segmentation and registration in orthodontia, the human-machine interaction and the three-dimensional modelling using MS Kinect in diagnostics and treatment of human motion disorders and neurological diseases. Associated comments include remarks and references to the development of modern computational tools, biosensors, wireless communication and data fusion used in assistive technologies and robotic systems. Mathematical tools common to all these applications form the next part of the paper that includes notes to spectral analysis, functional transforms, digital filtering, image enhancement, classification of multi-dimensional signal components and optimization using neural networks. Final remarks emphasize the interdisciplinary significance of the digital signal processing forming the integrating basis of many diverse research areas.

***Index Terms*—** history of digital signal and image processing, computational intelligence, digital signal processing methods, computer aided biomedical diagnostics and treatment, Microsoft Kinect three-dimensional modelling

1. INTRODUCTION

Digital signal processing (DSP) represents a general interdisciplinary area [1, 2, 3, 4, 5] based upon numerical or symbolical analysis of one-dimensional or multi-dimensional data sets that may stand for any physical, engineering, biomedical, technological, biological, acoustic, seismic or economical variable measured or observed with a given sampling period. Selected applications and goals of their processing are presented in Fig. 1. Even though applications cover completely different areas the mathematical background of their analysis is very close allowing processing of vectors, matrices or multi-dimensional arrays of observed data in a general way. Digital signal processing methods thus form an integrating platform for many diverse research branches.

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Fundamental mathematical methods of signal, image and multi-dimensional objects processing in the space and frequency domains include the following main topics

- Space domain signal processing and three-dimensional modelling
- Probabilistic and Bayesian signal processing
- Adaptive signal processing
- Space-frequency domain analysis
- Space-scale analysis and multidimensional signal decomposition and reconstruction

Selected mathematical methods cover basic numerical methods, statistical methods, adaptive methods including neural networks, discrete Fourier transform and discrete wavelet transform.

Goals of signal analysis cover the estimation of its characteristic parameters either in the *time* or *transform* domain. In some cases of signal processing *deterministic methods* may be applied but in many applications *statistical* and *adaptive methods* must be used to compensate for the incomplete knowledge of the real system time variations. Latest applications are devoted to human-machine interactions [6].

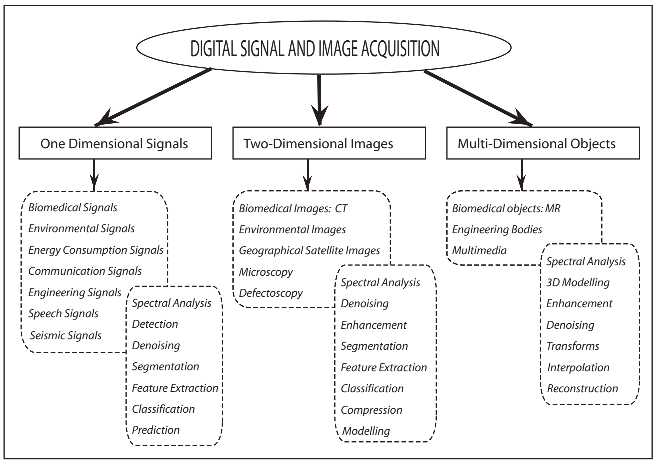


Fig. 1. Fundamental applications of one-dimensional and multi-dimensional signal processing and selected goals of their analysis

2. DIGITAL SIGNAL PROCESSING EVOLUTION

Historical roots of digital signal processing are very old. According to several researchers [7] they date back to the 25th century BC and they are related to the "Palermo stone" (Fig. 2) with earliest records of Nile's floods observed on the time base of 12 months (naive sampling). Processing of these records was concentrated to prediction of floods fundamental for watering fields. "Nilometers" used later were arabic buildings with instruments measuring the water level to predict climate conditions and to calculate taxes related to the prosperity of the country.

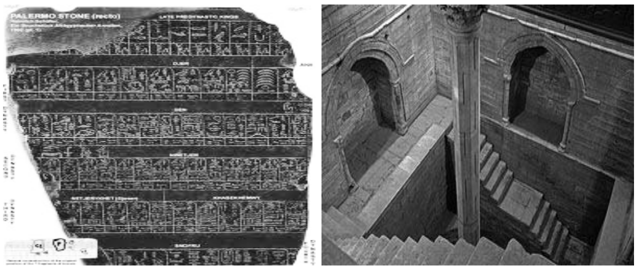


Fig. 2. Palermo stone (25th cent.BC) with records of the water level and nilometers on the Rawda Island Cairo (861 AD)

Isaac Newton, 1 Jan. 1643 – 31 March 1727

The mathematical fundamentals of digital signal and image processing methods are based upon *numerical analysis* that predates the invention of modern computers by many centuries using works of famous mathematicians including that of Isaac Newton (1643-1727), Joseph Louis Lagrange (1736-1813) and Leonhard Euler (1707-1783). The *matrix theory* introduced in the middle of the 19th century incorporating ideas of Gottfried Wilhelm Leibnitz (1646-1716) and Carl Friedrich Gauss (1777-1855) forms now one of its basic mathematical tools as well.

Jean Baptiste Joseph Fourier, 21 March 1768 – 16 May 1830

The theory of digital signal and image processing is in many cases closely connected with the *Fourier representation* of functions suggested in 1822 by Jean Baptiste Joseph Fourier (1786-1830), functional transforms, matrix theory and numerical methods including the *method of the least squares* presented independently by Carl Friedrich Gauss (1777-1855) and Adrien-Marie Legendre (1752-1833) at the beginning of the 19th century.

Marc-Antoine Parseval, 27 Apr. 1755 – 16 Aug. 1836

Relation between the space and frequency domain signal representation was then studied by Marc-Antoine Parseval (1755-1836). Basic mathematical methods were later extended to many fields including functional transforms (Pierre-Simon Laplace, 1749-1827), the estimation theory and stochastic processes introduced by Norbert Wiener (1894-1964) in 1949 and Rudolf E. Kalman (1930-) with applications in various areas covering adaptive filtering problems and spectrum analysis. Many algorithms use properties of the discrete Fourier transform and their implementation is enabled by its fast version published by James Cooley (1926-) and John Tukey (1915-2000) [8] in 1965. Modern statistical and Bayesian signal processing methods are based upon the research of Peter J. W. Rayner (1941-), Bill Fitzgerald (1948-2014) and many further researchers.

Johann Karl August Radon, 16 Dec. 1887 - 25 May 1956

Research of Johann Karl August Radon (1787-1956) formed the basis of computer tomography and opened a completely new area of biomedical image analysis. The following research of wavelet transform using the first known wavelet proposed by Alfred Haar (1885-1933) in 1909 is based upon research of Ingrid Daubechies (1954-) published in 1992 [9] followed by research of Martin Vetterli (1957-), Nick Kingsbury (1950-) and further researchers extending the principle of uncertainty discussed by Werner Heisenberg (1901-1976). The latest research related to computational intelligence allows the use of computer technologies for human-machine interaction, robotic systems and assistive technologies using different biosensors, data fusion and wireless communication systems.

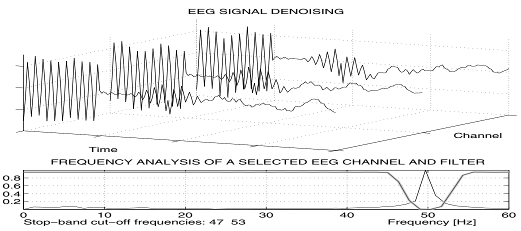
3. SELECTED CASE STUDIES

3.1. Analysis of Brain Activities

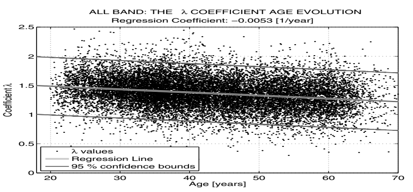
Analysis of EEG multichannel signals form the fundamental information source of brain activities. Its de-noising, segmentation and signal components classification is often used for diagnosis of different diseases. Age-related changes in the energy [10] and colored noise evolution [11, 12] presented in Fig. 3 can be used to explain learning ability and intellectual performance changes.

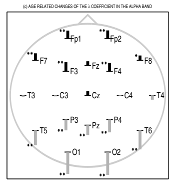
Further EEG analysis can be used to study mental activities [13], human-machine interaction and aging [14, 15, 16].

This topic is closely related also to robotic systems, assistive technologies, analysis of sport activities [17] and computational intelligence.



(a) De-noising of selected EEG channels





(b) Age-evolution of the colored noise (c) Regression

Fig. 3. Age-related changes in the EEG colored noise related to the power spectrum $1/f^{\lambda}$ distribution.

3.2. Classification of Muscle Disorders

Muscle activities are followed to detect neurological muscle disorders. Fig. 4 presents typical signals acquired for healthy and neuropathic individuals [18]. Their spectral features allow classification of negative and positive sets of individuals to enable more precise diagnosis. Neural networks can then be used to combine individual features and to improve sensitivity and specificity measures.

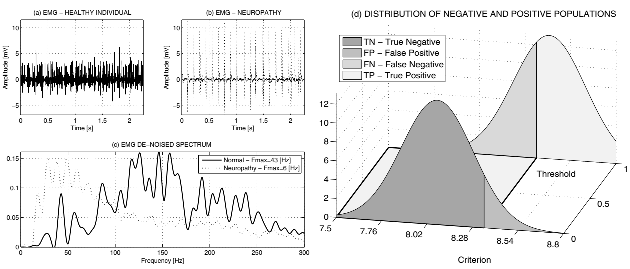


Fig. 4. Typical EMG signals of selected (a) healthy and (b) neuropathic individuals with (c) their smoothed spectra and (d) distribution of their spectral features.

3.3. Gait Features Extraction Using MS Kinect

Diagnostics of movement disorders including detection of gait features forms a very important neurological area using images and data from different biosensors, accelerometers and camera systems. An example of the MS Kinect use [19] for gait features acquisition is presented in Fig. 5, Image and depth sensors of this system enable to obtain image frames and detection of joints in the three-dimensional space. Digital filtering and data analysis was then used for detection of stride length and speed velocity [20] as main features used to detect Parkinson's disease.

The spatial modelling using both complex video systems and much more simple Kinect device can be used both for diagnostical purposes and for rehabilitation. This approach has a wide range of applications in medicine, neurology, engineering and robotics using human-machine interaction and computational intelligence.

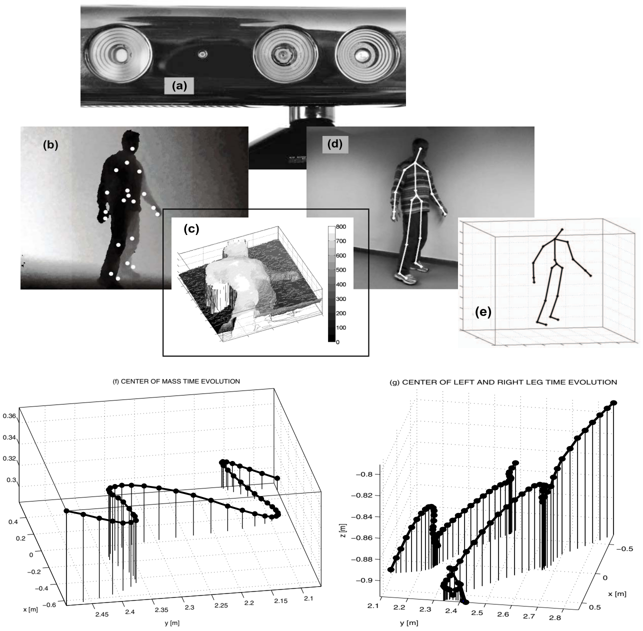
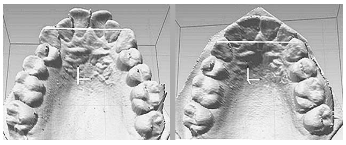


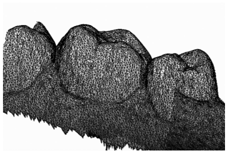
Fig. 5. MS Kinect use for 3D modelling presenting (a) MS Kinect sensors, (b), (c) the depth sensor map, (d) selected RGB camera frame, (e) the 3D skeleton model in MATLAB and data processed including the evolution of (f) the center of gravity of the body, and (g) centers of individual legs.

3.4. Segmentation and Three-Dimensional Modelling in Orthodontia

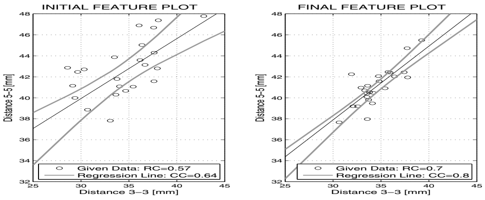
Digital modelling plays and important role in the orthodontic treatment replacing classical plaster casts by they digital models [21, 22]. Digitalization of plaster casts are performed either by the 3D scanning or by processing of their stereophotos allowing to use numerical methods for evaluation of specific measures of dental arch [23, 24]. To detect individual image components it was necessary to apply image de-noising and segmentation methods including watershed transform, region growing and Hough transform to evaluate distances between individual teeth before and after the treatment according to Figs 6(a) and (b). The 3D scanner allows to construct the digital model according to Figs 6(b).

Image registration forms another important area allowing to evaluate the progress of the treatment using digital models obtained either by digitalization of plaster casts or acquired through magnetic resonance systems.





(a) Plaster casts of the orthodontic arch (b) Digital model



(c) Distances between selected teeth during the treatment

Fig. 6. Image processing and spatial digital modelling methods in the orthodontic treatment.

4. MATHEMATICAL METHODS

The digital signal processing forms an integrating environment for many biomedical and engineering areas as it allows the use of similar mathematical methods for analysis and processing of observed multidimensional and multichannel signals and data fusion of information obtained.

Let us have the data sequence $\{x(n)\}_{n=0}^{N-1}$ of N values observed with the sampling frequency f_s standing for the (biomedical) signal or an image in case that data values are represented by vectors. Then it is possible to detect its frequency components by its discrete Fourier transform

$$X(k) = \sum_{k=0}^{N-1} x(x)\ \exp(-j\ kn\ 2\ \pi/N) \tag{1}$$

for $k = 0, 1, 2, \cdots, N$. Alternatively the wavelet transform can be used for signal or image decomposition.

Signal de-noising and enhancement must be applied in the next stage in most cases. In the simplest case and time-domain processing it is possible to use finite or infinite impulse response digital filters of the Mth order in the time domain to evaluate a new sequence

$$y(n) = -\sum_{k=1}^{M} a(k)\ y(n-k) + \sum_{k=0}^{M} b(k)\ x(n-k) \tag{2}$$

for $n = M, M+1, \cdots, N$. Alternatively it is possible to use frequency domain filtering or theresholding of wavelet coefficients and signal reconstruction.

Signal segmentation, selection of features, their classification and evaluation of results for the positive and negative sets of individuals is the most common problem of signal processing in medicine, neurology and in specific engineering applications.

Let us have a matrix $\mathbf{P}_{R,Q}$ of R features/attributes $\mathbf{p}_j$ (stride length, walking speed, age, ...) for each separate individual $j=1, 2, \cdots, Q$. Let us define further the associated row vector $\mathbf{t}_{1,Q}$ that specifies the class $c_k,\ k = 1, 2, \cdots, M$ of each individual selected from the given set of M classes. During the following learning process, a function that transforms the space of features $\mathbf{P}_{R,Q}$ into the vector $\mathbf{t}_{1,Q}$ specifying the classes is estimated.

The goal of the probabilistic classification is to find the estimate of class $\hat{c}_k$ of the unknown instance $\mathbf{p}$:

$$\hat{c}_k = \max_{c_1, c_2, \cdots, c_M} (P(c_k|\mathbf{p})) \tag{3}$$

The alternative approach is based upon supervised classification process using the two layer neural network structure with sigmoidal transfer functions $F1, F2$ that evaluates networks output $\mathbf{A2}$ by relations

$$\mathbf{A1}_{S1,Q} = F1(\mathbf{W1}_{S1,R}\ \mathbf{P}_{R,Q},\ \mathbf{b1}_{S1,1}), \tag{4}$$

$$\mathbf{A2}_{S2,Q} = F2(\mathbf{W2}_{S2,S1}\ \mathbf{A1}_{S1,Q},\ \mathbf{b2}_{S2,1}). \tag{5}$$

for the associated vector of target values $\mathbf{t}_{1,Q}$. During the optimization process coefficients $\mathbf{W1}, \mathbf{b1}, \mathbf{W2}, \mathbf{b2}$ are optimized to have networks output as close as possible to target values.

Classification systems in medicine include in most cases (i) the selection of characteristic features acquired by different biosensors, (ii) the learning process to allow their classification, and (iii) proposal of the diagnosis of an unknown individual with as high probability as possible.

More detail analysis allow correlation of these features with further environmental variables, control of robotic systems and the use of assistive technologies including rehabilitation.

5. CONCLUSION

The paper presents specific aspects of digital signal and image processing methods in the frame of historical evolution of this interdisciplinary area. In this way it follows ideas of Gottfried Wilhelm Leibniz (1646-1716), German mathematician and philosopher, who wrote papers about philosophical aspects of differentiation and integration of sciences [25].

G. Leibnitz discussed problems of too specialized disciplines and problems of scientists who lost abilities to communicate together. From this point of view the digital signal and image processing forms an integrating platform allowing to use similar mathematical tools for analysis of completely different problems using general mathematical tools for sampled data processing.

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