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Biosignal Processing and Analysis using Mathcad® - Pedagogical and Research Issues -

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Abstract—**Biosignal processing and analysis is generally perceived by many students to be a challenging topic to understand, and to become adept with the necessary analytical skills. This is a direct consequence of the high mathematical content involved, and the many abstract features of the topic. The Mathcad® package offers an excellent algorithm development environment for teaching biosignal processing and analysis modules, and can also be used effectively in many biosignal, and indeed bioengineering, research areas. In this paper, traditional introductory and advanced biosignal processing (and analysis) syllabi are reviewed, and the use of Mathcad® for teaching and research is illustrated with a number of examples.**

I. INTRODUCTION

Biomedical signal and image processing, or simply biosignal processing, encompasses those topics concerned with the signal processing, now primarily digital signal processing (DSP), of any biomedical or biomedical-related signal or image. Such signals arise from one of the many biomedical systems (biosystems) in the human body, listed in Table 1, and may be divided into the endogenous and exogenous varieties, listed in Table 2.

Generally speaking, in recent decades the topic of DSP has grown to be a very important field of study, both theoretically and technologically, and it now has many wide and diverse applications, not only in bioengineering, but also in the industrial, defence and commercial sectors. This growth has impacted on an ever-increasing demand for quality graduates, who are well-versed in the relevant DSP disciplines of mathematics, computing, electronics and algorithm engineering.

From a bioengineering perspective, many undergraduate and postgraduate degree programmes available at major universities, offer at least one biosignal processing module as part of their degree syllabus. This clearly illustrates the importance attached to biosignal processing as an integral part of a good bioengineering degree.

TABLE 1
THE MAJOR BIOMEDICAL SYSTEMS

Auditory	Circulatory	Digestive
Glucoregulatory	Immune	Nervous
Olfactory	Reproductive	Respiratory
Visual		

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TABLE 2
THE MAJOR ENDOGENOUS AND EXOGENOUS BIOSIGNALS

Endogenous Biosignals	Exogenous Biosignals
Electrocardiogram (ECG)	Event-Related Potentials (ERPs)
Electroencephalogram (EEG)	General Ultrasound
Electromyogram (EMG)	Doppler Ultrasound
Nerve Action Potentials	Computed Tomography (CT)
Muscle Force	X-Rays
Blood Pressure	
Temperature	
Respiration	
Hormone Concentrations	
Blood Glucose Concentrations	
Otoacoustic Emissions	
Magnetic Resonance Imaging (MRI)	
Positron Emission Tomography (PET)	

However, although curriculum requirements, career aspirations, professional advancement, and intellectual opportunities, have made DSP an important field of study, the subject is generally perceived by present-day students to be difficult to understand conceptually, and to become adept with the necessary analytical skills. This is due, in part, to the high mathematical content of signal processing modules, which many students have great difficulty understanding; a political consequence of lower student intake standards and inappropriate mathematics curricula in schools. However, it also reflects the many abstract, though essential, features of the subject. From a pedagogical viewpoint, a major criticism raised by students is that the content of a signal processing module is “too dry and has nothing to do with the real world”. Although this may have certain foundations in a poor, overworked lecturer’s lack of drive, enthusiasm and imagination (!!), the traditional DSP learning experience is often criticised by students for being too passive, inanimate and non-interactive.

In this new millennium, with the explosion of knowledge, skills and understanding required by the modern graduate in DSP, technology-based approaches have been introduced. These approaches are variously described as technology-based teaching/education (TBT/TBE) or more commonly as computer-based teaching/education (CBT/CBE). We will use "CBE" in the remainder of this paper.

CBE approaches for teaching DSP include the use of multimedia, internet and world wide web (the Web), student-driven interactive experiments, distance teaming and firmware-based laboratory sessions [1]. To augment these approaches, a number of high-level DSP packages have been introduced into curricula, including the highly popular LabVIEW®, MATLAB®, and Mathcad® environments. These approaches have also proved to be very effective in project work – both for short-term curriculum-based projects, and long-term funded research projects.

This paper reviews traditional introductory and advanced biosignal processing (and analysis) syllabi, and surveys the various CBE approaches which have been introduced for teaching the topic, and for project work. It is based on the authors' teaching of biosignal processing for almost 20 years at the Bioengineering Unit, University of Strathclyde, Glasgow (http://www.strath.ac.uk/bioeng/). Emphasis is given to the Mathcad® algorithm development software, and examples are included showing the use of Mathcad® for teaching foundation and advanced topics, and also for research.

II. THE BIOSIGNAL PROCESSING SYLLABUS

A. General Comments

In order to compile an effective and efficient biosignal processing module within an undergraduate or postgraduate bioengineering syllabus, it is important to carefully address the constituent components of the module, within the constraints of a limited budget, limited resources, student entry qualifications, student mathematical ability, student workload, and timetabling considerations.

B. Mathematical Competence

Students have a wide range of mathematical abilities. For postgraduate students, this is a reflection, in part, of the variety of first degrees that they have acquired. For example, a student with a first degree in electronic engineering will generally have a higher mathematical ability than a student whose first degree is in physiotherapy. In order to accommodate such a wide variety of student abilities, it is important that any biosignal processing module is not too mathematically-intensive, but emphasises the principal concepts. This could be difficult for such a notoriously difficult topic as signal processing, which some have correctly described as "just applied mathematics", however with the advent of high-level programming tools such as LabVIEW®, MATLAB® and Mathcad®, students can gain much better insights into the Fourier transform, for example, than from just paper mathematical analysis.

C. Topic Coverage

The range of topics encompassed by biosignal processing is quite extensive. However, it may be divided into the following major areas:

(a) Origin and nature of physiological signals (ECG; EEG; EMG; ERP).
(b) Signals and systems (linear systems theory; Laplace, Fourier and *z*-transforms; signal conversion; DFT and FFT).
(c) Signal processing (analogue filters; digital filters; FIR design).
(d) Advanced signal processing (adaptive techniques; time-frequency and wavelet analysis; fuzzy logic; artificial neural networks).
(e) Origin and nature of medical images (CT; MRI; ultrasound).
(f) Image processing (enhancement; restoration; compression; segmentation).
(g) Biosignal processing (e.g. ECG/EEG analysis, MRI segmentation).

To cover all of the above topics in depth is generally not possible due to time limitations and student workload. However, a solid grounding in foundation topics (e.g. signals & systems) is usually given, together with an overview of the more advanced topics (e.g. time-frequency analysis), in order that students will at least have heard of these and be aware of their potential applications.

D. Laboratory Exercises

Laboratory classes should form an integral part of the module. These classes should be designed such that students can have access to a variety of physiological signals which they can manipulate and analyse. Signals may be obtained from databases or the students themselves, the latter using one of the commercially available biomedical signal acquisition systems. Obviously, the appropriate ethics and safety guidelines and procedures have to be adhered to. Alternatively, acquisition systems may be designed and built by the students as part of an electronic systems module, thus integrating two key modules.

III. DATABASES AND ACQUISITION SYSTEMS

A. Databases

A variety of excellent physiological and medical image databases are now freely available for downloading appropriate data for analysis:

- http://www.physionet.org/ The PhysioNet site has a large collection of recorded physiological signals and related open-source software. It also enables the user to generate his/her own synthesized signals.
- http://www.bic.mni.mcgill.ca/brainweb Brainweb enables a variety of MR brain images to be simulated and downloaded.
- http://www.cma.mgh.harvard.edu/ibsr/ The internet brain segmentation repository (IBSR), provides manually-guided expert segmentation results along with clinical MR brain image data. Its purpose is to encourage the evaluation and development of segmentation methods.

B. DSP Packages and Acquisition Environments

A number of useful biosignal data acquisition systems have been developed, including the following:

- Biopac Student Lab® (www.biopac.com)
- Neuroscan® (www.neuro.com)
- BioRadio® (www.clevemed.com)

Many of these systems include physiological data acquisition electronics for recording ECG, EEG, EMG, EOG and PSG signals, along with software for real-time channel display, filtering and annotation. These systems can also be used for advanced student projects and research.

A variety of comprehensive high-level algorithm development and data acquisition packages/environments are also available, the most popular of which include the following:

- DigiScope [2] This useful package provides an environment for conducting physiological experiments, and designing a variety of filters. Visualisation tools are incorporated.
- National Instruments (http://www.ni.com/) This Company provides a range of data acquisition, test and measurement hardware, and also the LabVIEW® graphical programming development software.
- The MathWorks (http://www.mathworks.com/) This Company markets the very popular MATLAB® algorithm development suite of software, which includes a number of toolboxes (Signal Processing, Image Processing, Neural Networks) and Simulink, offering a comprehensive environment for high-level processing of biomedical signals and images. The company also offers a range of hardware, including the Data Acquisition Toolbox, which enables configuration of external hardware devices, and allows data to be read into MATLAB® for processing, analysis, and output. Also, the Image Acquisition Toolbox extends the MATLAB® technical computing environment with functions for acquiring video and images from PC-compatible frame-grabber cards and video devices. The toolbox also enables connection and configuration of hardware, video previewing, and streaming of images directly into MATLAB® for analysis and visualization.
- Mathsoft (http://www.mathsoft.com/) This Company markets the Calculation Management Suite®, which includes the ubiquitous Mathcad® software and associated Extension Packs (Data Analysis, Signal Processing, Image Processing, Wavelets, Solving and Optimization). Mathcad® can also interface with a range of analogue I/O boards from Measurement Computing and National Instruments, for real-time data acquisition.

IV. MATHCAD EXAMPLES

A. Mathcad®

Essentially, Mathcad® is analogous to an electronic scratchpad (maths-aware word processor), in which text and equations are entered on a worksheet, the latter in real math notation. Equations are automatically calculated and recalculated, together with automatic unit conversion and graphical display of results. Matrix and vector manipulation, together with symbolic algebra, are easily accommodated. Mathcad® files are readily publishable in a variety of formats: XML, HTML, PDF, and RTF and with the use of the *Mathcad® Application Server*, live maths may be published on the Web using existing Mathcad® worksheets.

B. Foundation Topic - Convolution

An example of a Mathcad® worksheet illustrating continuous-time convolution, is shown in Figure 1. In this example the student can investigate the convolution of an input rectangular signal and a triangular system impulse response. A slider provides the amount of translation involved in the convolution process, and the student can manipulate this and obtain a clear conception of the build-up to the convolution integral.

C. Foundation Topic - Fourier Transform

Figure 2 shows another example of a Mathcad® worksheet, in this case illustrating the genesis of the Fourier transform from the Fourier series. Here, a periodic rectangular wavetrain is provided, together with the magnitudes and phases of the complex exponential Fourier coefficients. The student can then manipulate the fundamental period T_0 of the wavetrain using the slider, and observe the effect this has on the Fourier series line spacing. Of course in the limit as the period approaches infinity, the blue line spectrum will eventually become the red continuous spectrum.

D. Advanced Topic - Image Processing

An example of image processing, specifically histogram modification of an MR image, is illustrated in Figure 3. In this case the original lower right image is subjected to a grey-level transformation function to produce the "enhanced" image at the top left. The student can select a variety of transformation functions.

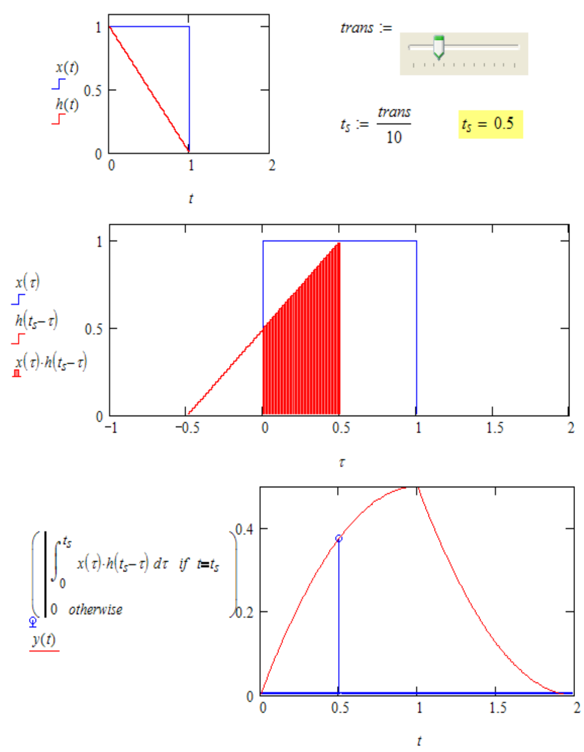

Fig. 1. Mathcad worksheet illustrating the processes involved for continuous-time convolution.

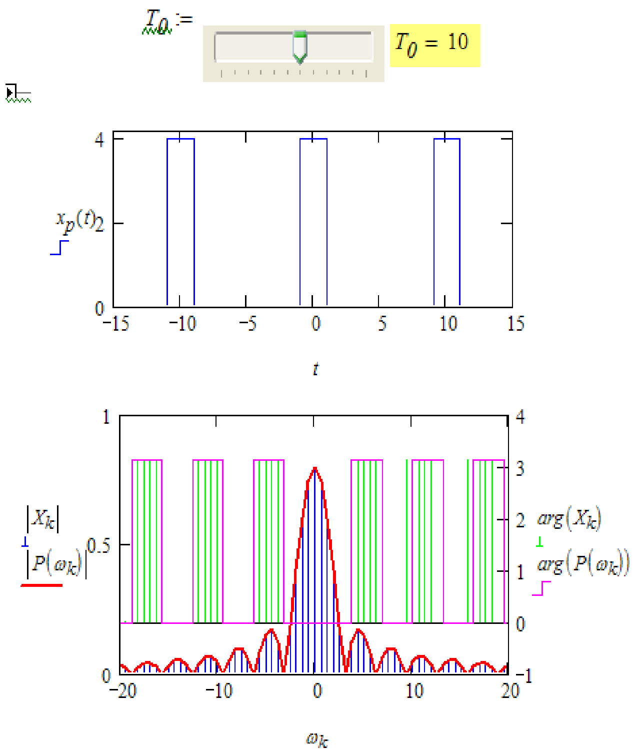

Fig. 2. Mathcad worksheet illustrating the development of the Fourier transform of a pulse, by considering the complex exponential Fourier series of a periodic rectangular pulse train as the period $T_0 \to \infty$. A student can manipulate the period using the slider at the top and observe changes in the blue line spectrum as it approaches the red Fourier transform.

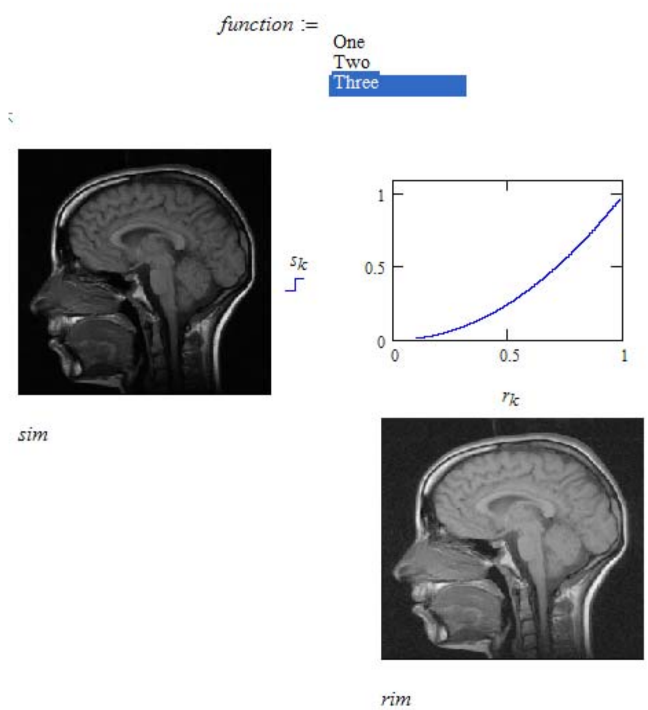

Fig. 3. Mathcad worksheet illustrating histogram modification of an MR image. The lower right image has its pixels modified according to the grey-level transformation function, to produce the upper left enhanced image.

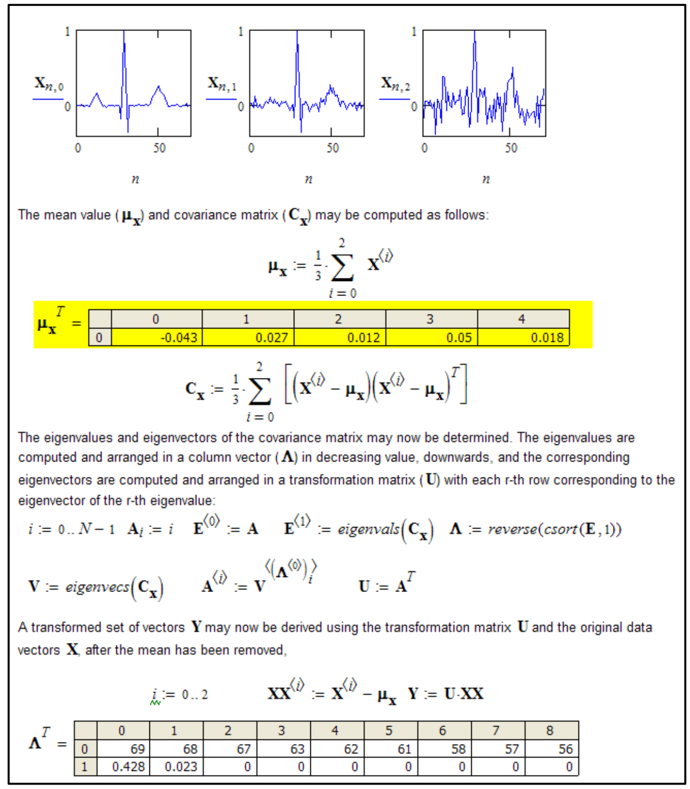

Fig. 4. Mathcad worksheet illustrating ECG compression using PCA. Three ECG waveforms are shown at the top, followed by live matrix mathematics. The effect of retaining fewer eigenvalues in the reconstruction process results in a higher compression but also an increase in noise.

E. Research Topic - ECG Data Compression

The final Mathcad® example concerns the research topic of ECG compression using principal component analysis (PCA) [3]-[4]. A worksheet illustrating this is shown in Figure 4.

V. CONCLUSIONS

Due to the wide-ranging mathematical abilities of students, the teaching of biosignal processing should be conceptual in nature, and emphasise the techniques and underlying methodologies, rather than heavy mathematical details. The Mathcad® package offers an excellent environment to achieve this, and is also an ideal paradigm for algorithm development in biosignal research.

REFERENCES

[1] W. A. Sandham, and A. J. Anderson, "Computer-based DSP education," *Proc. ISSC-98, Irish Signals and Systems Conference*, 25-26 June 1998, Dublin Institute of Technology, Dublin, Ireland, pp. 143-150, 1998.

[2] W. J. Tompkins (Ed.), *Biomedical Digital Signal Processing*. Englewood Cliffs NJ: Prentice Hall, 1993.

[3] D. J. Hamilton, W. A. Sandham, and J. McQueen, "Recognition in a heartbeat," *IEE Electronics Systems and Software Magazine*, vol. 3, no. 4, pp. 24-29, August/September 2005.

[4] D. J. Hamilton, J. McQueen, and W. A. Sandham, "Improved PCA-based electrocardiogram data compression using variable-length asymmetric beat vectors," *Applied Signal Processing*, vol. 6, pp. 194-202, 1999.