Signals and Systems in Biomedical Engineering

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Description of Computer Demonstrations

A set of computer programs accompany this book. They are at http://extras.springer.com. They are written in Java and can be run in most operating systems found on desktop computers, Linux, Microsoft Windows, MacOS, and SunOS. These programs were used to generate most of the figures used in the text. In keeping with the theme of the book, the programs are interactive and allow the user to conduct virtual experiments. The programs are grouped chapterwise for chapters. A program for data acquisition and real-time analysis is also provided for the additional chapter. Please refer to the corresponding chapters for detailed theory and background for the programs.

The programs are Java Applets and need to have the Java Run-time Environment (JRE) installed on your computer system. The JRE is freely available from Sun Microsystems and can be downloaded from their website, http://java.sun.com. Java Applets run in a Web Browser and enjoy all the security features used by your system. The programs for the additional chapter require data acquisition using the computer sound card, and you will have to enable this by setting the Java Policy, using "policytool" in your Java installation.

All the programs have a help page that can be invoked by clicking on any gray area of the program window ("gray area" is any area without graphs or buttons).

Brief description of each program is given below; for more details see the *help pages* in the program.

For detailed discussions on the techniques and models used in the programs refer to the corresponding chapters in the book, "Signals and Systems in Biomedical Engineering".

Chapter 1

1.1 ECG measurement, modeling and simulation:

This program shows the ECG recorded from two of the primry limb leads, lead I and lead II. This is the measurement of the ECG.

Using the Einthoven triangle this data is used to calculate the cardiac vector. Einthoven's assumption of an equilateral triangle for the limb leads is used. This is the model used for data interpretation. Geometric calculation of the cardiac vector is shown animated in real-time. . Simulation of any of the other leads in the frontal plane can be selected by the user.

Chapter 2

2.1 Non-linearity in measurement systems

A program to illustrate input-output non-linearity in a system. The user first selects an input signal. This signal's amplitude and offset can be adjusted. The user can choose high pass filtering to remove the offset. However, if the offset is amplified before the filtering, then the signal can saturate before the filtering. The static characteristic of the system through which the signal passes can be controlled by the user. The linearity can be varied and the gain or sensitivity can also be changed. The user can study the effect of non-linearity, gain, and signal offset on the output.

2.2 Biopotential recording

This program illustrates the recording of a biopotential signal using a pair of electrodes. A stationary time-varying potential or a longitudinally moving potential can be selected as the source. Two electrodes connected in differential configuration provide a bipolar recording output.

The electrode spacing can be adjusted by the user. Both the monopolar (single electrode) and bipolar signals are displayed. A simulated powerline EMI interference (50 Hz) is added to the signal picked up at the electrodes. The user can adjust electrode geometry to see the effect on the signal. The amplifier common-mode rejection ratio (CMRR) can be adjusted - this also affects the quality of noise rejection. A 50 Hz notch filter can be selected.

Chapter 3

3.1 Signals

In this program a time varying signal is displayed. When the signal is "paused", the displayed block of data is used to demonstrate time shift, time reversal, and time scaling. This program introduces the idea of grabbing a block of signal from a continuous real-world process, and subjecting it to basic operations.

3.2 Systems

This is a basic demonstration of an input-output system. Signals can be subjected to simple algebraic processing in a system, providing the concept of a system with input and output and properties like linearity, causality and invertibility.

3.3 Convolution demonstration

This program illustrates the convolution operation. The user chooses an input signal for study. The system properties can be adjusted by the user, and the impulse response of the selected system is displayed. The program calculates the output of the system by convolution using the impulse response.

3.4 Convolution calculation

The calculation of convolution is demonstrated graphically. It shows an animated convolution calculations using the two methods discussed in the chapter text. The first method is the addition of scaled and time shifted impulse responses, and the second method is the integration of the product of the input and the time reversed and shifted impulse response.

3.5 Fourier series of time signals

This program demonstrates the Fourier Series by combining sinusoids to form arbitrary signals under user control. This program has 30 pairs of scroll bars to control the amplitude and phase of thirty sinusoids whose frequencies are multiples of the first sinusoid. The sum of the sinusoids is displayed to demonstrate the Fourier Series as the process of combining sinusoids. Preset values for some common physiological signals are provided.

3.6 Two Dimensional Fourier series

While one-dimensional sinusoids are familiar figures, higher dimensional sinusoids are harder to understand. This program shows the projection of 2-D sinusoids using grayscale intensity to indicate amplitude.The program illustrates combinations of such 2-D sinusoids to form images. The comparison with 1-D Fourier series is useful.

Chapter 4

4.1 Filters: LPF, HPF, BPF, Notch

This program demonstrates a selection of filters. The frequency plots of the filters are displayed. The user can adjust filter parameters like the cutoff frequency.The user can select an input signal, can add noise to the signal, and see the effect of filtering on noise removal and on signal degradation. The basic filter types discussed in the text are available. Filter parameters like the cutoff frequency can be adjusted by the user.

4.2 Filter design

The same filters as in the previous program have their frequency plots displayed, and in addition the pole-zero plot is also displayed. Adjustment of the filter parameters by the user is accompanied by corresponding changes in the frequency plots and the pole-zero plots. The locus of the poles with changes in filter parameters gives insight into the design process.

4.3 Ensemble averaging

This program generates a noisy evoked potential at regular intervals. The latency of the evoked potential can be adjusted by the user. In the lower panel of the display, the ensemble average of the signal is continuously updated. If the signal latency is not constant then the ensemble averaging is not very effective. An optional weighted ensemble average is also provided. This has a decreasing weight for earlier data; therefore it is preferable for time varying signals, but otherwise its noise removal is weaker than normal ensemble averaging.

4.4 Feedback control

This program simulates a simple first order plant with and without feedback control. The user controls the input to this system. The plant being a first order system, its response is sluggish. The system with feedback control using a PID controller is shown in the lower half of the screen. The feedback control can considerably improve the dynamic characteristics of the plant output. Adjusting the controller parameters can be seen to improve the speed of system response.

Chapter 5

5.1 Sampling and quantization

The user can select a signal, and then choose a sampling rate and quantization size in this program. The effect of these on the appearance of the sampled signal as well as on the quality of reconstruction can be studied. Three options are available for the reconstruction filter: "Zero-Order Hold", "Linear Interpolation" and "Low Pass Filter (8th order elliptic)". The ZOH produces the effect of the output of a D/A converter. The linear interpolation simulates the display usually created on standard computer screen outputs. The elliptic LPF simulates an analogue elliptic filter (8th order) which can be realized as an electronic circuit. The following section describes the LPF reconstruction filter. .

The transfer function of the analogue filter with normalized cutoff at 1 rad/sec is:

$$H_A(s) = \frac{H_o(s^2 + A_{01})(s^2 + A_{02})(s^2 + A_{03})(s^2 + A_{04})}{(s^2 + B_{11}s + B_{01})(s^2 + B_{12}s + B_{02})(s^2 + B_{13}s + B_{03})(s^2 + B_{14}s + B_{04})}$$

with

$H_0 = 0.002876322$

$A_{01} = 14.34825$	$B_{01} = 0.2914919$	$B_{11} = 0.8711574$
$A_{02} = 2.231643$	$B_{02} = 0.6123726$	$B_{12} = 0.4729136$
$A_{03} = 1.320447$	$B_{03} = 0.8397386$	$B_{13} = 0.1825141$
$A_{04} = 1.128832$	$B_{04} = 0.9264592$	$B_{14} = 0.04471442$

This analogue filter is transformed into a digital filter using the bilinear transform, using a sampling frequency 2.2 times the filter cutoff, so that we have a filter with cutoff at 0.45 times the sampling rate. This filter, therefore, is a reasonable analogue approximation to the desired low pass filter cutting off at half the sampling rate,

The digital filter transfer function is:

$$H_D(s) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + a_4 z^{-4} + a_5 z^{-5} + a_6 z^{-6} + a_7 z^{-7} + a_8 z^{-8}}{b_0 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + b_4 z^{-4} + b_5 z^{-5} + b_6 z^{-6} + b_7 z^{-7} + b_8 z^{-8}}$$

with constants,

$a_0 = 1.26997150832$	$b_0 = 1.00$
$a_1 = -7.41679239932$	$b_1 = -7.0576457511$
$a_2 = 20.599881616$	$b_2 = 22.1218833488$
$a_3 = -35.6624835417$	$b_3 = -40.1834194704$
$a_4 = 42.4399025785$	$b_4 = 46.23278032338$
$a_5 = -35.6624835417$	$b_5 = -34.4835159314$
$a_6 = 20.599881616$	$b_6 = 16.2770371973$
$a_7 = -7.41679239932$	$b_7 = -4.44446856755$
$a_8 = 1.26997150832$	$b_8 = 0.537410118753$

5.2 Sampling Theorem and Quantization Error

This program is similar to the previous one. It allows the user to select a signal, and also select the sampling rate and quantization bits as in the previous program. In addition, the simulated Fourier transform of the continuous time signal and the Discrete-Time Fourier Transform of the sampled signal are also shown. This allows the user to simultaneously see sampling in the time and frequency domains. The quantization error is also displayed.

Chapter 6

6.1 DFT calculation

This program demonstrates the calculation and some applications of the Discrete Fourier Transform. The user can choose a signal and see its DFT magnitude. The inverse DFT with zero-padding illustrates the idea of time interpolation using the Fourier domain.

6.2 Power spectrum calculation

This program demonstrates calculation of the frequency spectrum for stationary as well as time varying signals. The user chooses an input signal and the power spectrum calculated by averaging periodograms can be displayed. The short-time Fourier transform can also be calculated and displayed in this program for comparison with the block calculation of the spectrum.

Input signals for Spectrum calculations

There are five signals to choose from. The ECG and Aortic pressure are digitized waveforms of one cardiac cycle and repeated cyclically. The third signal called an "EP-signal" is a synthetic signal with a sharp spike and a broad slow wave; this is repeated with irregular timing (the time interval to the next event is a random variable). The fourth is a sinusoid with selectable frequency. The fifth input signal that is available is a synthetic "EEG" signal.

EEG signal

The EEG signal is generated as follows. A pseudo-random signal is first generated by an autoregressive model.

$$x[n] = 0.37\,x[n-1] - 0.24\,x[n-2] - 0.18\,x[n-3] - 0.25\,x[n-4] + w[n] \tag{1}$$

where $w[n]$ is a zero mean uniformly distributed random signal between $-0.5 < w < +0.5$. This signal is then passed through a high-pass filter and low pass filter with transfer functions:

$$H_1(s) = \frac{s^2/\omega_1^2}{1 + s(1.414/\omega_1) + s^2/\omega_1^2}$$

where $\omega_1 = 2\pi f_1$ with $f_1 = 8\,Hz$.

$$= H_2(s) = \frac{1}{1 + s(2\zeta/\omega_2) + s^2/\omega_2^2} \tag{2}$$

The EEG state is a variable that describes a hypothetical change of brain state from "alert" to "relaxed". It is a numerical variable, $1 < m < 13$.

$\omega_2 = 2\pi f_2$, with $f_2 = 8 + m$, and $\zeta = 0.3 + \frac{m}{24}$.

Window Functions

A choice of Windows is available. The Hamming window is defined in the text. The Bartlett window is a triangular function defined as:

$$w[n] = \begin{cases} 1 - 2\left(\frac{|n|}{N_1-1}\right) & 0 \leq n < N_1 \\ 0 & N_1 \leq n < N \end{cases} \tag{3}$$

The Blackman window is similar to the Hamming window and is defined as:

$$w[n] = \begin{cases} 0.42 - 0.5\cos\left(\frac{2\pi n}{N_1-1}\right) + 0.08\cos\left(\frac{4\pi n}{N_1-1}\right) & 0 \leq n < N_1 \\ 0 & N_1 \leq n < N \end{cases} \tag{4}$$

6.3 Wavelet decomposition

This program demonstrates the wavelet transform with a choice of input signals, and a choice of wavelets. One wavelet transform can be applied at time to a selected signal. The wavelet transform can be displayed as separate wavelet levels plotted against time, or as a frequency versus coefficient amplitude similar to the Fourier spectrum.

Chapter 7

7.1 Graphics, animation & gait analysis

This program demonstrates the use of 3-D representation and animation. It presents a simple 3-D stick figure display of a few cycles of walking. The viewing angle can be adjusted by the user. The 3-D stick figure is projected to the viewing plane. In addition to the stick figure of the limbs, the muscles involved in walking can be selected for viewing by the user. When the muscles are active their color becomes red, otherwise it is gray.

7.2 Solid Models & Gait Analysis

This program is an enhanced version of the animated walking figure of the previous program. The sticks representing the limb segments are drawn as cylinders. Muscles are drawn as ellipsoids. The user can choose the viewing position and speed of display. The program can also simulate the camera or viewer "panning" the walking figure by fixing the center of view on either the pelvis or ankle. The activity of the muscles is shown as change in color. The data set was recorded in the Gait Lab in the Rehabilitation Institute of Christian Medical College, Vellore.

Chapter 8

8.1 Hodgkin-Huxley Model of the AP

This program is a straightforward implementation of the Hodgkin-Huxley model. The user can set the stimulus parameters. Repeated stimulation can be delivered to observe the effect of the refractory period.

8.2 Voltage clamp

This program is a simulation of the voltage clamp experiment. The user can apply the voltage clamp and observe the ionic currents. The gain of the feedback can be adjusted to see the importance of the instrumentation on the quality of the observed signals.

8.3 Fluctuation analysis

A patch clamp experiment with user selectable electrode tip size (or patch size), and voltage clamp is simulated in this program. The patch current recorded by the electrode is displayed. The power spectrum of the channel fluctuation is also displayed. A curve is drawn for manually fitting to the data; the mean amplitude is automatically calculated, while the corner frequency is adjustable by the user.

8.4 Action Potential propagation

The spatio-temporal action potential in a long axon is simulated in this program. The location of stimulation is under user control, so the user can stimulate at any point along the length of the axon. The user can also select the transmembrane potential at one point on the axon for highlighting. When the display is paused, the ionic currents corresponding to this point on the axon are displayed; a cursor is also presented for the user to take time measurements when the display is paused.

Chapter 9

9.1 Electrical Stimulation

The tissue stimulation model described in the book is simulated numerically in this program. The user can set the electrode geometry and the nerve depth. The spatio-temporal transmembrane potential is displayed. The conditions for generation of an action potential can be studied.

9.2 Magnetic Stimulation

This program implements a numerical simulation of magnetic stimulation of a nerve embedded inside a tissue volume. A circular coil is used for stimulation, and the coil parameters and stimulus parameters can be adjusted. The stimulus signal is the discharge of a capacitor through the coil, and therefore is an RLC discharge. The waveform is a damped sinusoid. Adjusting the value of the resistance in the circuit changes the damping. The coil position and orientation can be changed to study their effect on the excitation of the nerve. The effect of these parameters on the spatio-temporal transmembrane potential and action potential can be studied using this program.

9.3 Triple stimulation

The triple stimulation technique described in the book can be best understood by using a multi-nerve simulation. This program uses a 5 nerve bundle and each nerve incorporates a spatio-temporal action potential model. This bundle of nerves can be stimulated at three points. Brain stimulation results in asynchronous action potentials propagating distally, while the other two points of stimulation results in synchronous action potentials. The triple stimulation technique shows how we can obtain a CMAP representing a synchronous volley from the brain.

Chapter 10

10.1 Sarcomere length-tension

This program shows a cartoon simulation showing the sliding filament model. The thick and thin filaments of a sarcomere are shown animated while its parent muscle is activated and bears a load. The user can adjust the level of muscle activity and the load. The length-tension curve for the passive and active muscle are also drawn.

10.2 Muscle force generation

This is an implementation of the linearized muscle model described in the book. Summation and tetanus can be studied in this simulation.

10.3 Muscle experiment

This program uses the linearized model to simulate a typical introductory laboratory practical on skeletal muscle. The length-tension behavior of muscle can be studied using this program.

Chapter 11

11.1 Motor Unit Action Potential

This program simulates a motor unit, and the motor unit action potential (MUAP) recorded by bipolar electrodes of adjustable geometry. The user can select the number of fibers in a motor unit and the electrode geometry to simulate an MUAP. The fiber location and end-plate distribution are generated using random numbers with distributions as discussed in the book.

11.2 EMG Simulation

This program implements the EMG model described in the book and provides a detailed simulation of the voluntary EMG. The user can select either a surface electrode pair or a needle electrode. In the case of a needle electrode, the user can control insertion of the needle. The level of muscle activity is selected by the user. Several analysis techniques for the EMG are available. An audio output of the EMG is also output if the sound card output is enabled. Models of pathology are also incorporated as discussed in the book.

Chapter 12

12.1 Joint reflex control

This program simulates the elbow joint articulated by the extensor triceps surae muscle and the flexor biceps brachii muscle. A cartoon of the musculoskeletal structure with almost real-time movement is presented graphically to make the virtual experiment realistic. Forces are represented as masses (weight, or balloon) for simplicity of drawing Relative sizes of skeleton, muscle length, tendon length are correctly drawn. Several parameters of the reflex loop can be adjusted by the user.

The following parameters are used.

Body weight = 60kg, Height = 1.8 m

Humerus: Length from point of muscle origin to fulcrum = 0.33 m (x_b)

Distances of points of insertion from the joint = 0.033 m (x_1, x_2)

Nominal muscle fibre length=0.20 m, nominal tendon length = 0.12 m

Forearm mass = 1.3 kg (0.022 × body weight)

Center of Gravity of forearm = 0.46 × 0.33 m = 0.15 m from elbow

Moment of Inertia of the forearm about the elbow = $1.3 \times (0.33 \times 0.827)^2 = 0.0968\,\text{kg}\ m^2$

Muscle force (muscle cross-sectional area=50 cm^2, force/area=24 N/cm^2) total force = 1200 N

Neuronal activity: Signal strengths are used in the simulation calculations. For simulation display the neural signal strengths are converted to frequency modulated impulse sequences. The neuronal firing is that of a pool of neurons, the firing rate shown is merely proportional to such a pool.

The intrafusal fibres length-tension curve is similar to the extrafusal fibres, with the level of activity being given by the γ activation. For simplicity a single exponential function has been assumed, with the curvature determined by the γ activity.

$$L_i(t) = \left(\mathrm{e}^{\gamma L_m/20}\mathrm{e}^{L_m/20}\right)/400,\ I_a(t) = 10L_i + 20\frac{dL_i(t)}{dt}$$

For the muscle impulse response in the book by the equation $m(t) = k_m e^{-t/\tau_m} u(t)$ assuming a time constant of 0.03 s for the muscle, the muscle function corresponds to a first order low-pass function with cutoff of 5 Hz.

For a given set of neural inputs and load value, the elbow angle can b calculated by solving the equations given in the text.The numerical solution of the joint position is prone to calculation errors when the CW and CCW moment values are very close. This can produce calculation instabilities epecially at the extreme joint positions.

Subject voluntary movement "Experimenter" controls – external load or force application, tendon tap, pull/push, imposing cyclical movement.

A cartoon of the musculoskeletal structure with almost real-time movement helps to make the virtual experiment realistic. Forces are represented as masses (weight, or balloon) for simplicity of drawing Relative sizes of skeleton, muscle length, tendon length are correctly drawn.

Chapter 13

13.1 Firing Rate analysis

The user of this program can generate action potential impulse sequences by selecting an input signal - sinusoidal or manually adjusted. The different types of demodulation techniques discussed in the correspoonding chapter of the book are available - constant value between pulses, linear interpolation between pulses, low-pass filter demodulation. Ideal pass-band low-pass filtering as well as causal second order filters are available. The demodulation filter parameters can be controlled by the user.

Additional Chapter

Data Acquisition and Real-Time Signal Processing

A.1 Data acquisition on the PC

This program uses the sound card on the PC to acquire signals from two channels. Using additional hardware described in the book, a physiological signal like the EMG can be acquired for analysis. Standard analysis like Spectrum analysis, and Rectified Mean Value, are available in this program for online analysis.