1 Introduction

1.1 Biosignals Much of the activity in biomedical engineering, be it clinical or research, involves the measurement, processing, analysis, display, and/or generation of biosignals. Signals are variations in energy that carry information, and the search for information from living systems has been a preoccupation of medicine since its beginnings (Figure 1.1). This chapter is about the modification of such signals to make them more useful or more informative. To this end, this chapter presents tools and strategies that use digital signal processing to enhance the information content or interpretation of biosignals. The variable that carries information (the specific energy fluctuation) depends on the type of energy involved. Biological signals are usually encoded into variations of electrical, chemical, or mechanical energy, although, occasionally, variations in thermal energy are of interest. For communication within the body, signals are primarily encoded as variations in electrical or chemical energy. When chemical energy is used, encoding is usually done by varying the concentration of the chemical within a “physiological compartment,” for example, the concentration of a hormone in blood. Bioelectric signals use the flow or concentration of ions, the primary charge carriers within the body, to transmit information. Speech, the primary form of communication between humans, encodes information as variations in pressure. Table 1.1 summarizes the different types of energy that can be used to carry information and the associated variables that encode this information. Table 1.1 also shows the physiological measurements that involve these energy forms. Outside the body, information is commonly transmitted and processed as variations in electrical energy, although mechanical energy was used in the seventeenth and early eighteenth centuries to send messages. The semaphore telegraph used the position of one or more large arms placed on a tower or high point to encode letters of the alphabet. These arm positions could be observed at some distance (on a clear day) and relayed onward if necessary. Information processing can also be accomplished mechanically, as in the early numerical processors constructed by Babbage. Even mechanically based digital components have been attempted using variations in fluid flow. Modern electronics provides numerous techniques for modifying electrical signals at very high speeds. The body also uses electrical energy to carry information when speed is important. Since the body does not have many free electrons, it relies on ions, notably Na^+, K^+, and Cl^-, as the primary charge carriers. Outside the body, electrically based signals are so useful that signals carried by other energy forms are usually converted into electrical energy when significant transmission or processing tasks are required. The conversion of physiological energy into an electric signal is an important step, often the first step, in gathering information for clinical or research use. The energy conversion task is done by a device termed a transducer,* specifically, a biotransducer. The biotransducer is usually the most critical component in systems designed to measure biosignals.
Table 1.1 Energy Forms and Associated Information-Carrying Variables Energy Variables (Specific Fluctuation) Common Measurements Chemical Chemical activity and/or concentration Blood ion, O_2, CO_2, pH, hormonal concentrations, and other chemistry Mechanical Position Force, torque, or pressure Muscle movement, cardiovascular pressures, muscle contractility, valve, and other cardiac sounds Electrical Voltage (potential energy of charge carriers) Current (charge carrier flow) EEG, ECG, EMG, EOG, ERG, EGG, and GSR Thermal Temperature Body temperature and thermography

With the exception of this chapter, this book is limited to topics on digital signal and image processing. To the extent possible, each topic is introduced with the minimum amount of information required to use and understand the approach along with enough information to apply the methodology in an intelligent manner. Strengths and weaknesses of the various methods are also explored, particularly through discovery in the problems at the end of the chapter. Hence, the problems at the end of each chapter, most of which utilize the MATLAB® software package (Waltham, MA), constitute an integral part of the book and a few topics are introduced only in the problems. A fundamental assumption of this book is that an in-depth mathematical treatment of signal-processing methodology is not essential for effective and appropriate application of these tools. This book is designed to develop skills in the application of signal-and image-processing technology, but it may not provide the skills necessary to develop new techniques and algorithms. References are provided for those who need to move beyond the application of signal- and image-processing tools to the design and development of new methodology. In the subsequent chapters, the major topics include sections on implementation using the MATLAB software package. Fluency with the MATLAB language is assumed and is essential for the use of this book. Where appropriate, a topic area may also include a more in-depth treatment, including some of the underlying mathematics.

1.2 Biosignal Measurement Systems

Biomedical measurement systems are designed to measure and usually record one or more biosignals. A schematic representation of a typical biomedical measurement system is shown in **Figure 1.2**. The term biomedical measurement is quite general and includes image acquisition and the acquisition of different types of diagnostic information. Information from the biological process of interest must first be converted into an electric signal via the *transducer*. Some analog signal processing is usually required, often including amplification and lowpass (or bandpass) filtering. Since most signal processing is easier to implement using digital methods, the analog signal is converted into a digital format using an analog-to-digital converter (ADC). Once converted, the signal is often stored or *buffered* in the memory to facilitate subsequent signal processing. Alternatively, in *real-time* applications, the incoming data are processed as they come in, often with minimal buffering, and may not be permanently stored. Digital signal-processing algorithms can then be applied to the digitized signal. These signal-processing techniques can take on a wide variety of forms with varying levels of sophistication and they make up the major topic areas of this book. In some applications such as diagnosis, a classification algorithm may be applied to the processed data to determine the state of a disease or the class of a tumor or tissue. A wide variety of classification techniques exist and the most popular techniques are discussed in **Chapters 16** and **17**. Finally, some sort of output is necessary in any useful system. This usually takes the form of a display, as in imaging systems, but it may be some type of effector mechanism such as in an automated drug delivery system. The basic elements shown in **Figure 1.2** are discussed in greater detail in the next section.

Figure 1.2 Schematic representation of a typical biomedical measurement system.

* Learning the vocabulary is an important part of mastering a discipline. In this book, the commonly used terms are highlighted using italics. Sometimes, the highlighted term is described when it is introduced, but occasionally, the determination of its definition is the responsibility of the reader.

1.3 Transducers

A transducer is a device that converts energy from one form to another. By this definition, a lightbulb or a motor is a transducer. In signal-processing applications, energy is used to carry information; the purpose of energy conversion is to transfer that information, not to transform energy as with a lightbulb or a motor. In measurement systems, all transducers are so-called input transducers: they convert nonelectrical energy into an electronic signal. An exception to this is the electrode, a transducer that converts ionic electrical energy into electronic electrical energy. Usually, the output of a biomedical transducer is voltage (or current) whose amplitude is proportional to the measured energy (**Figure 1.3**).

Input transducers use one of the two different fundamental approaches: the input energy causes the transducer element to generate voltage or current, or the input energy creates a change in an electrical property (the resistance, inductance, or capacitance) of the transducer material. Most optical transducers use the first approach. Photons strike a photo sensitive material producing free electrons (or holes) that can then be detected as external current flow. Piezoelectric devices used in ultrasound also generate a charge when under mechanical stress. Many examples can be found in the use of the second category, a change in some electrical property. For example, metals (and semiconductors) undergo a consistent change in resistance with changes in temperature and most temperature transducers utilize this feature. Other examples include the strain gage, which measures mechanical deformation using the small change in resistance that occurs when the sensing material is stretched.

The energy that is converted by the input transducer may be generated by the physiological process itself, it may be energy that is indirectly related to the physiological process, or it may be energy produced by an external source. In the last case, the externally generated energy interacts with, and is modified by, the physiological process and it is this alteration that produces the measurement. For example, when externally generated x-rays are transmitted through the body they are absorbed by the intervening tissue and a measurement of this absorption is used to construct an image. Many diagnostically useful imaging systems are based on this external energy approach.

Figure 1.3 General systems representation of a transducer.

2.1 Biosignals

This book concerns digital signals, but we often think about these signals in terms of their analog equivalents. Most of the concepts presented apply equally well to analog or digital signals, the analytical operations performed on both are similar, and there is a correspondence between the equations for these similar digital and analog operations. Often both equations are presented to emphasize this similarity. Since most of the examples and problems are carried out in MATLAB on a computer, they are implemented in the digital domain even if they are phrased as analog domain problems.

Digital signals can be classified into two major subgroups: *linear* and *nonlinear* (**Figure 2.1**). Linear signals derive from linear processes while nonlinear signals arise from nonlinear processes such as chaotic or turbulent systems. Each of these two signal classes can be further divided into *stationary* and *nonstationary* signals. Stationary signals have consistent statistical properties over the data set being analyzed. There is a formal mathematical definition of stationarity based on the signal's probability distribution function, but basically stationary signals have constant means, standard deviations, and the same average correlations between data points. It is important to know which type of signal you are dealing with, as the analytical tools that apply are quite different. **Figure 2.1** indicates the chapters that cover signal-processing tools appropriate to the various signal types.

Much of this book is devoted to signals that are linear and stationary since an extensive set of powerful signal-processing tools has been developed for these signals. While biological signals are often nonlinear and nonstationary, these tools are so useful that assumptions or approximations are made so that linear techniques can be applied. Linearity can be approximated by using small-signal conditions where many systems behave more-or-less linearly. Alternatively, piecewise linear approaches can be used where the analysis is confined to operating ranges over which the system behaves linearly. For nonstationary signals that have a varying mean, *detrending* techniques that subtract out the time-varying mean can be used. A popular approach to dealing with nonstationary signals is to study the signal within a time frame or series of time frames that are short enough so that the signal can be considered stationary during that period. When an assumption or approximation of linearity is clearly untenable, several nonlinear signal-processing tools are available as described in **Chapters 10** and **11**. These nonlinear signals are often assumed to be stationary as their analysis requires long data sets. For this reason, nonlinear signal processing is particularly challenging for nonstationary signals.

Figure 2.1 Classification of digital signals. The chapters that cover the different signal types are shown.

2.1.1 Signal Encoding

Concepts covered in this book are applied to signals that already exist in digital format; the assumption is that they have been detected by a biotransducer, appropriately preprocessed, and correctly converted to digital signals (see **Section 1.6**). All signals involve some type of encoding scheme. Encoding schemes vary in complexity: human speech is so complex that decoding can still challenge voice recognition computer programs. Yet the same information can be encoded into a simple series of long and short pulses known as the Morse code, easily decoded by a computer.

Most encoding strategies can be divided into two broad categories or domains: continuous and discrete. The discrete domain is used almost exclusively in computer-based technology, as such signals are easier to manipulate electronically. Discrete signals are usually transmitted as a series of pulses at even (synchronous transmission) or uneven (asynchronous transmission) intervals. These pulses may be of equal duration, or the information can be encoded into the pulse length. Within the digital domain, many different encoding schemes can be used. For encoding alphanumeric characters, those featured on the keys of a computer keyboard, the ASCII code is used. Here each letter, the numbers 0 through 9, and many other characters are encoded into an 8-bit binary number. For example, the letters a through z are encoded as 97 (for a) through 122 (for z) while the capital letters A through Z are encoded by numbers *65*through 90. The complete ASCII code can be found on numerous Internet sites.

In the continuous domain, information is encoded in terms of signal amplitude, usually the intensity of the signal at any given time. For an *analog* electronic signal, this could be the value of the voltage or current at a given time. Note that all signals are by nature *time varying*, since a single constant value contains no information.* For example, the temperature in a room can be encoded so that 0 V represents 0.0°C, 5 V represents 10°C, 10 V represents 20°C, and so on. Assuming a *linear* relationship, the encoding equation for the transducer would be:

This equation relating the input (temperature) to the output (voltage) follows the classic linear relationship:

where *m* is the slope of the input-output relationship and *b* is the offset which in this case is 0.0. The temperature can be found from the voltage output of the transducer as

Analog encoding was common in consumer electronics such as early high-fidelity amplifiers and television receivers, although most of these applications now use discrete or digital encoding. (Vinyl records that are still in vogue among some audiophiles are notable exceptions.) Nonetheless, analog encoding is likely to remain important to the biomedical engineer, if only because many physiological systems use analog encoding, and most biotransducers generate analog encoded signals.

When a continuous analog signal is converted into the digital domain, it is represented by a series of numbers that are discrete samples of the analog signals at specific points in time (see **Section 1.6.2**):

Usually this series of numbers would be stored in sequential memory locations with $x[1]$ followed by $x[2]$ then $x[3]$, and so on. In this case, the memory index number, n, relates to the time associated with a given sample. Converting back to relative time is achieved by multiplying the index number, n, by the sampling interval (**Equation 1.5**), repeated here:

Recall that it is common to use brackets to identify a discrete variable (i.e., $x[n]$), and standard parentheses to notate an analog variable (i.e., $x(t)$). The MATLAB programming also uses brackets, but in a somewhat different context: to define a series of numbers (e.g., `x = [2 4 6 8]`).

* Modern information theory makes explicit the difference between information and meaning. The latter depends upon the receiver, that is, the device or person for which the information is intended. Many students have attended lectures with a considerable amount of information that, for them, had little meaning. This book strives valiantly for information with the expectation that it will also have meaning.

2.1.2 Signal Linearity, Time Invariance, Causality

In the example of a transducer defined by **Equation 2.1**, the relationship between input temperature signal and output voltage signal was assumed to be linear. The concept of linearity has a rigorous definition, but the basic concept is one of proportionality. If you double the input into a linear system, you will double the output. One way of stating this proportionality property mathematically is: if the independent variables of linear function are multiplied by a constant, k, the output of the function is simply multiplied by k:

Also, if f is a linear function:

In addition, if $y = f(x)$ and $z = df(x)/dx$, then