Chapter 1
INTRODUCTION TO DIGITAL SIGNAL PROCESSING
1.8 Digital Filters
1.9 Three DSP Applications

Victoria, BC, Canada
Email: aantoniou@ieee.org

August 5, 2018

- Digital filters began to be mentioned in the literature during the 1960s.

- Digital filters began to be mentioned in the literature during the 1960s.

- With the dramatic advancements in digital technologies, digital filters began to offer viable economical solutions to many of the filtering problems of the past.

  However, it was soon realized that digital filters could also perform filtering tasks that were not even possible with analog filters.

Introduction

- Digital filters began to be mentioned in the literature during the 1960s.

- With the dramatic advancements in digital technologies, digital filters began to offer viable economical solutions to many of the filtering problems of the past.

  However, it was soon realized that digital filters could also perform filtering tasks that were not even possible with analog filters.

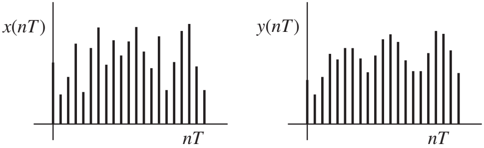
- Since that time a great variety of digital filters have been invented such as nonrecursive, recursive, and adaptive filters.

Introduction

- Digital filters began to be mentioned in the literature during the 1960s.
- With the dramatic advancements in digital technologies, digital filters began to offer viable economical solutions to many of the filtering problems of the past.

  However, it was soon realized that digital filters could also perform filtering tasks that were not even possible with analog filters.
- Since that time a great variety of digital filters have been invented such as nonrecursive, recursive, and adaptive filters.
- This presentation will examine the advantages and disadvantages of digital filters and their unique features, the types of digital filters that have evolved as well as their applications.

- In its most general form, a digital filter is a system that will receive an input in the form of a discrete-time signal and produce an output again in the form of a discrete-time signal.



- There are many types of discrete-time systems that will receive a discrete-time signal as input and produce a processed discrete-time signal as output, e.g.,
  - digital control systems,
  - data-compression systems,
  - encoders and decoders.

- There are many types of discrete-time systems that will receive a discrete-time signal as input and produce a processed discrete-time signal as output, e.g.,
  - digital control systems,
  - data-compression systems,
  - encoders and decoders.
- What differentiates digital filters from other discrete-time systems is the nature of the processing involved.

  As in analog filters, the spectrum of *the output signal must be related to that of the input by some rule of correspondence.*

Historical Background

The roots of digital filters go back in history to the 1600s when the astronomers of that time were attempting to rationalize and interpret their measurements of planetary orbits.

- The need arose in those days for a process that could be used *to interpolate a function represented by numerical data,* and a wide range of numerical interpolation formulas were proposed over the years by Gregory (1638-1675), Newton (1642-1727), Taylor (1685-1731), Stirling (1692-1770), Lagrange (1736-1813), Bessel (1784-1846).

Historical Background

The roots of digital filters go back in history to the 1600s when the astronomers of that time were attempting to rationalize and interpret their measurements of planetary orbits.

- The need arose in those days for a process that could be used *to interpolate a function represented by numerical data,* and a wide range of numerical interpolation formulas were proposed over the years by Gregory (1638-1675), Newton (1642-1727), Taylor (1685-1731), Stirling (1692-1770), Lagrange (1736-1813), Bessel (1784-1846).
- On the basis of interpolation formulas, formulas were soon generated that would perform numerical differentiation or integration on a function represented by numerical data.

Historical Background *Cont'd*

- Consider the situation where a numerical algorithm is used to compute the derivative of a signal $x(t)$ at $t = t_1, t_2, \ldots, t_K$, designated as $y(t)$, and assume that the signal is represented by its numerical values

$$x(t_1), x(t_2), \ldots, x(t_K)$$

- Consider the situation where a numerical algorithm is used to compute the derivative of a signal $x(t)$ at $t = t_1, t_2, \ldots, t_K$, designated as $y(t)$, and assume that the signal is represented by its numerical values

$$x(t_1), x(t_2), \ldots, x(t_K)$$

- In such a situation, the algorithm receives a discrete-time signal as input and produces a discrete-time signal

$$y(t_1), y(t_2), \ldots, y(t_K)$$

as output, which is a differentiated version of the input signal.

Historical Background *Cont'd*

- Consider the situation where a numerical algorithm is used to compute the derivative of a signal $x(t)$ at $t = t_1, t_2, \ldots, t_K$, designated as $y(t)$, and assume that the signal is represented by its numerical values

$$x(t_1), x(t_2), \ldots, x(t_K)$$

- In such a situation, the algorithm receives a discrete-time signal as input and produces a discrete-time signal

$$y(t_1), y(t_2), \ldots, y(t_K)$$

  as output, which is a differentiated version of the input signal.

- Since differentiation is essentially a filtering process, as was demonstrated earlier on, an algorithm that performs numerical differentiation is, in fact, a digital filtering process.

- Interpolation formulas were put to good use during the 1600s and 1700s for the construction of numerical tables of all forms for use in business, commerce, engineering, navigation etc., for example, logarithmic and trigonometric tables.

Historical Background *Cont'd*

- Interpolation formulas were put to good use during the 1600s and 1700s for the construction of numerical tables of all forms for use in business, commerce, engineering, navigation etc., for example, logarithmic and trigonometric tables.

- In fact, it was the great need for accurate numerical tables that prompted Charles Babbage during the 1800s to embark on his lifelong quest to automate the computation process through *his famous difference engines*, and it is on the basis of numerical formulas that his machines were supposed to perform their computations.

- The purpose of Babbage's machines was to evaluate polynomials of the form

$$y = f(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n$$

based on a simple numerical extrapolation algorithm.

- The purpose of Babbage's machines was to evaluate polynomials of the form

$$y = f(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n$$

based on a simple numerical extrapolation algorithm.

- Given a series of values of x, say,

$$x_1,\ x_2,\ \ldots,\ x_K$$

these machines were designed to calculate the numerical values of the polynomial

$$y(x_1),\ y(x_2),\ \ldots,\ y(x_K)$$

- In other words, a difference engine would receive a series of numbers as input and produce a series of numbers as output and, contrary to popular belief, these machines were, in effect, *discrete-time systems*.

- In other words, a difference engine would receive a series of numbers as input and produce a series of numbers as output and, contrary to popular belief, these machines were, in effect, *discrete-time systems*.

- More information on the roots of DSP can be found in a two-part article published by the author in: IEEE Circuits and Systems Magazine, issues no. 1 and no. 4, 2007.

  Presentations based on these articles can be found at the following links:

  http://www.ece.uvic.ca/~andreas/RLectures/RootsDSP-PartI-Pres.pdf

  http://www.ece.uvic.ca/~andreas/RLectures/RootsDSP-PartII-Pres.pdf

- Numerical methods have found their perfect niche in the modern digital computer and considerable progress has been achieved through the 50s and 60s in the development of algorithms that can be used to process signals represented in terms of numerical data.

Historical Background *Cont'd*

- Numerical methods have found their perfect niche in the modern digital computer and considerable progress has been achieved through the 50s and 60s in the development of algorithms that can be used to process signals represented in terms of numerical data.

- By the late 50s, a cohesive collection of techniques referred to as *data smoothing and prediction* began to emerge through the efforts of pioneers such as Blackman, Bode, Shannon, Tuckey, and others.

Historical Background *Cont'd*

- Numerical methods have found their perfect niche in the modern digital computer and considerable progress has been achieved through the 50s and 60s in the development of algorithms that can be used to process signals represented in terms of numerical data.
- By the late 50s, a cohesive collection of techniques referred to as *data smoothing and prediction* began to emerge through the efforts of pioneers such as Blackman, Bode, Shannon, Tuckey, and others.
- During the early 60s, an entity referred to as the *digital filter* began to appear in the literature to describe a collection of algorithms that could be used for spectral analysis and data processing.

- In 1965, Blackman authored a book titled *Data Smoothing and Prediction* and included in this work certain techniques which he referred to as *numerical filtering*.

  This was the first book on DSP and what he referred to as 'numerical filtering' is known today as digital filtering.

- In 1965, Blackman authored a book titled *Data Smoothing and Prediction* and included in this work certain techniques which he referred to as *numerical filtering*.

  This was the first book on DSP and what he referred to as 'numerical filtering' is known today as digital filtering.

- Within a year, in 1966, Kaiser authored a landmark chapter, titled *Digital Filters* in a book by Kuo titled *System Analysis by Digital Computer* in which he presented a collection of signal processing techniques that could be applied for the simulation of dynamic systems and analog filters.

- In 1965, Blackman authored a book titled *Data Smoothing and Prediction* and included in this work certain techniques which he referred to as *numerical filtering*.

  This was the first book on DSP and what he referred to as 'numerical filtering' is known today as digital filtering.

- Within a year, in 1966, Kaiser authored a landmark chapter, titled *Digital Filters* in a book by Kuo titled *System Analysis by Digital Computer* in which he presented a collection of signal processing techniques that could be applied for the simulation of dynamic systems and analog filters.

- From the late 60s on, the analysis and processing of signals in the form of numerical data became known as *digital signal processing*, and algorithms, computer programs, or systems that could be used for the processing of these signals *became fully established as digital filters.*

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.
  - Accuracy is high.

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.
  - Accuracy is high.
  - Physical size is small.

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.
  - Accuracy is high.
  - Physical size is small.
  - Reliability is high.

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.
  - Accuracy is high.
  - Physical size is small.
  - Reliability is high.
  - Component drift is relatively unimportant.

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.
  - Accuracy is high.
  - Physical size is small.
  - Reliability is high.
  - Component drift is relatively unimportant.
  - The influence of electrical environmental noise is negligible.

Advantages of Digital Technologies

- With the rapid advances in integrated-circuit technology during the 60s, a trend towards digital technologies began to emerge to take advantage of the classical merits of digital systems in general, which are as follows:
  - Component tolerances are uncritical.
  - Accuracy is high.
  - Physical size is small.
  - Reliability is high.
  - Component drift is relatively unimportant.
  - The influence of electrical environmental noise is negligible.
- Because of all these important features, digital technologies can be used to design *cost-effective, reliable, and versatile systems.*

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.
- For example,

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.
- For example,
  - the telephone system was digitized through the use of pulse-code modulation and code-division multiple access systems;

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.
- For example,
  - the telephone system was digitized through the use of pulse-code modulation and code-division multiple access systems;
  - then came long-distance digital communications;

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.
- For example,
  - the telephone system was digitized through the use of pulse-code modulation and code-division multiple access systems;
  - then came long-distance digital communications;
  - then the music industry adopted digital methodologies through the use of compact disks, DVDs, and MP3 players;

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.
- For example,
  - the telephone system was digitized through the use of pulse-code modulation and code-division multiple access systems;
  - then came long-distance digital communications;
  - then the music industry adopted digital methodologies through the use of compact disks, DVDs, and MP3 players;
  - then came high-definition digital TV and digital radio;

Applications of Digital Technologies

- The numerous advantages of digital technologies led to an uninterrupted revolution from the early 60s on which continues to this date whereby analog systems are continuously being replaced by corresponding digital systems.
- For example,
  - the telephone system was digitized through the use of pulse-code modulation and code-division multiple access systems;
  - then came long-distance digital communications;
  - then the music industry adopted digital methodologies through the use of compact disks, DVDs, and MP3 players;
  - then came high-definition digital TV and digital radio;
  - and so on.

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters
  - Recursive filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters
  - Recursive filters
  - Fan filters

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters
  - Recursive filters
  - Fan filters
  - Two-dimensional filters

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters
  - Recursive filters
  - Fan filters
  - Two-dimensional filters
  - Adaptive filters

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters
  - Recursive filters
  - Fan filters
  - Two-dimensional filters
  - Adaptive filters
  - Multidimensional filters

Types of Digital Filters

- Digital filters in hardware form began to appear during the late 60s and two early designs were reported by Jackson, Kaiser, and McDonald in 1968 and Peled and Liu in 1974.
- Research on digital filters continued through the years and a great variety of filter types have evolved, as follows:
  - Nonrecursive filters
  - Recursive filters
  - Fan filters
  - Two-dimensional filters
  - Adaptive filters
  - Multidimensional filters
  - Multirate filters

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

– Communications systems

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

- Communications systems
- Audio systems such as CD players

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

- Communications systems
- Audio systems such as CD players
- Instrumentation

The applications of digital filters are widespread and include but are not limited to the following:

– Communications systems
– Audio systems such as CD players
– Instrumentation
– Image processing and enhancement

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

- Communications systems
- Audio systems such as CD players
- Instrumentation
- Image processing and enhancement
- Processing of seismic and other geophysical signals

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

- Communications systems
- Audio systems such as CD players
- Instrumentation
- Image processing and enhancement
- Processing of seismic and other geophysical signals
- Processing of biological signals

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

- Communications systems
- Audio systems such as CD players
- Instrumentation
- Image processing and enhancement
- Processing of seismic and other geophysical signals
- Processing of biological signals
- Artificial cochleas

Applications of Digital Filters

The applications of digital filters are widespread and include but are not limited to the following:

- Communications systems
- Audio systems such as CD players
- Instrumentation
- Image processing and enhancement
- Processing of seismic and other geophysical signals
- Processing of biological signals
- Artificial cochleas
- Speech synthesis

Software and Hardware Implementations

It is nowadays convenient to consider computer programs and digital hardware that can perform digital filtering as two different implementations of digital filters, namely,

- software digital filters, and

Software and Hardware Implementations

It is nowadays convenient to consider computer programs and digital hardware that can perform digital filtering as two different implementations of digital filters, namely,

- software digital filters, and
- hardware digital filters.

- Software digital filters can be implemented in terms of a high-level language, such as C++ or MATLAB, on a personal computer or workstation or by using a low-level language on a general-purpose digital signal-processing chip.

Software and Hardware Implementations *Cont'd*

- Software digital filters can be implemented in terms of a high-level language, such as C++ or MATLAB, on a personal computer or workstation or by using a low-level language on a general-purpose digital signal-processing chip.
- Hardware digital filters can be designed using a number of highly specialized interconnected VLSI chips.

- Software digital filters can be implemented in terms of a high-level language, such as C++ or MATLAB, on a personal computer or workstation or by using a low-level language on a general-purpose digital signal-processing chip.
- Hardware digital filters can be designed using a number of highly specialized interconnected VLSI chips.
- Both hardware and software digital filters can be used to process real-time or nonreal-time (recorded) signals, except that the former are usually much faster and can deal with real-time signals whose frequency spectrums extend to much higher frequencies.

- Occasionally, digital filters are used in so-called *quasireal-time applications* whereby the processing appears to a person to be in real time although, in actual fact, the samples of the signal are first collected and stored in a digital memory and are then retrieved in blocks and processed.

- Occasionally, digital filters are used in so-called *quasireal-time applications* whereby the processing appears to a person to be in real time although, in actual fact, the samples of the signal are first collected and stored in a digital memory and are then retrieved in blocks and processed.

- A familiar, quasireal-time application involves the transmission of radio signals over the Internet.

  The signals are transmitted through data packets in a rather irregular manner, yet the music appears to be continuous only because the data packets are first stored and then properly sequenced.

  This is why it takes a little while for the transmission to begin.

Hardware Implementations

- Hardware digital filters have an important advantage relative to analog filters, in addition to the classical merits associated with digital systems in general:

  The parameters of a digital filter are stored in a computer memory and, consequently, they can be easily changed in real time.

- Hardware digital filters have an important advantage relative to analog filters, in addition to the classical merits associated with digital systems in general:

  The parameters of a digital filter are stored in a computer memory and, consequently, they can be easily changed in real time.

- This means that digital filters are more suitable for applications where programmable, time-variable, or adaptive filters are required.

- Hardware digital filters are essentially low-frequency systems where the operating frequencies are in some range, say, 0 to ω_{max}, where ω_{max} is dependent on the state-of-the-art in VLSI technology and the application at hand.

- Hardware digital filters are essentially low-frequency systems where the operating frequencies are in some range, say, 0 to ω_{max}, where ω_{max} is dependent on the state-of-the-art in VLSI technology and the application at hand.
- At any instant, say, $t = nT$, a digital filter generates the value of the output signal through a series of computations using some of the values of the input signal and possibly some of the values of the output signal.

Hardware Implementations *Cont'd*

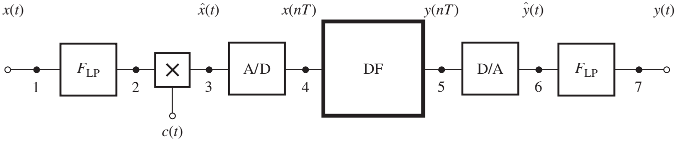
- Hardware digital filters are essentially low-frequency systems where the operating frequencies are in some range, say, 0 to ω_{max}, where ω_{max} is dependent on the state-of-the-art in VLSI technology and the application at hand.
- At any instant, say, $t = nT$, a digital filter generates the value of the output signal through a series of computations using some of the values of the input signal and possibly some of the values of the output signal.
- Once the sampling frequency is fixed, the sampling period $T = 2\pi/\omega_s$ is also fixed and, consequently, a basic limitation is imposed by the amount of computation that can be performed by the digital filter during period T.

- As the sampling frequency is increased, T is reduced, and the amount of computation that can be performed during period T is reduced.

- As the sampling frequency is increased, T is reduced, and the amount of computation that can be performed during period T is reduced.
- Eventually, at some sufficiently high sampling frequency ω_{max}, a digital filter will become computation bound and will malfunction.

- As the sampling frequency is increased, T is reduced, and the amount of computation that can be performed during period T is reduced.
- Eventually, at some sufficiently high sampling frequency ω_{max}, a digital filter will become computation bound and will malfunction.
- The upper frequency of applicability, ω_{max}, is difficult to formalize because it depends on several factors such as the number-crunching capability and speed of the VLSI chips used on the one hand, and the complexity of the filtering tasks involved on the other.

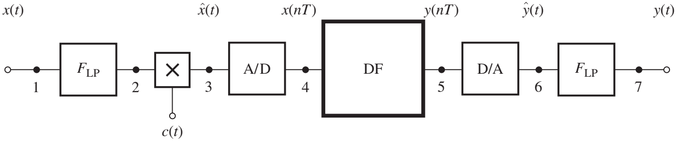
- Hardware digital filters are very competitive in applications where the signals are in discrete-time form.



- Hardware digital filters are very competitive in applications where the signals are in discrete-time form.

- However, they have certain disadvantages as well:

  For applications where the signals are of the continuous-time type, additional interfacing components are needed to make digital filters work, e.g., A/D and D/A converters.



Comparison of Filter Technologies

The choice of filter type depends on many factors and trade-offs and is critically dependent on the type of application but the key factor is the frequency range of operation:

- For frequencies less than, say, 20 kHz digital filters are most likely to offer the best engineering solution.

Comparison of Filter Technologies

The choice of filter type depends on many factors and trade-offs and is critically dependent on the type of application but the key factor is the frequency range of operation:

- For frequencies less than, say, 20 kHz digital filters are most likely to offer the best engineering solution.
- For frequencies between 20 kHz and 0.1 GHz, the choice is between
  - discrete-active *RC* filters,
  - switched-capacitor filters, and
  - passive *RLC* filters

Comparison of Filter Technologies

The choice of filter type depends on many factors and trade-offs and is critically dependent on the type of application but the key factor is the frequency range of operation:

- For frequencies less than, say, 20 kHz digital filters are most likely to offer the best engineering solution.
- For frequencies between 20 kHz and 0.1 GHz, the choice is between
  - discrete-active *RC* filters,
  - switched-capacitor filters, and
  - passive *RLC* filters
- For frequencies in the range 0.1 and 15 GHz, the choice is between an integrated active *RC* filter and a microwave filter.

Comparison of Filter Technologies

The choice of filter type depends on many factors and trade-offs and is critically dependent on the type of application but the key factor is the frequency range of operation:

- For frequencies less than, say, 20 kHz digital filters are most likely to offer the best engineering solution.
- For frequencies between 20 kHz and 0.1 GHz, the choice is between
  - discrete-active RC filters,
  - switched-capacitor filters, and
  - passive RLC filters
- For frequencies in the range 0.1 and 15 GHz, the choice is between an integrated active RC filter and a microwave filter.
- For frequencies in excess of 15 GHz, a microwave filter is the only choice.

Type of technology	**Frequency range**
Digital filters	0 to ω_{max}
Discrete active *RC* filters	10 Hz to 1 MHz
Switched-capacitor filters	10 Hz to 5 MHz
Passive *RLC* filters	0.1 MHz to 0.1 GHz
Integrated active *RC* filters	0.1 MHz to 15 GHz
Microwave filters	0.5 GHz to 500 GHz

Software Digital Implementations

- Note that *software digital filters have no counterpart in the analog world* and, therefore, for nonreal-time applications they are the only choice.

Software Digital Implementations

- Note that *software digital filters have no counterpart in the analog world* and, therefore, for nonreal-time applications they are the only choice.

- Software digital filters find widespread applications in almost every field of science and technology.

  The following two applications will illustrate what can be done:

  - Processing of EKG signals
  - Processing of stock exchange data

- An *electrocardiogram* (or EKG also referred to as ECG) of a healthy individual assumes a fairly well defined form although significant variations can occur from one person to the next as in fingerprints.

  Yet certain telltale patterns in an EKG enable a cardiologist to diagnose certain heart conditions.

Processing of EKG Signals

- An *electrocardiogram* (or EKG also referred to as ECG) of a healthy individual assumes a fairly well defined form although significant variations can occur from one person to the next as in fingerprints.

  Yet certain telltale patterns in an EKG enable a cardiologist to diagnose certain heart conditions.

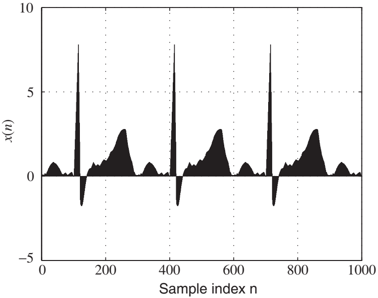
- An EKG is essentially a graph representing a low-level electrical signal picked up by a pair of electrodes attached to certain well defined points on the body and connected to an electrical instrument known as the *electrocardiograph*.

- Electrocardiographs are used in clinics and hospitals where a multitude of other types of electrical machines are utilized such as X-ray machines and electrical motors.

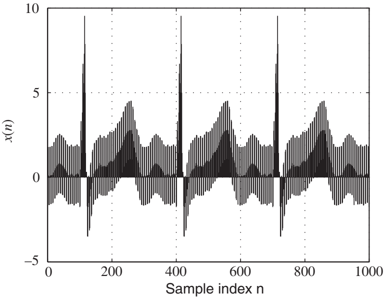
Processing of EKG Signals *Cont'd*

- Electrocardiographs are used in clinics and hospitals where a multitude of other types of electrical machines are utilized such as X-ray machines and electrical motors.
- All these machines along with the power lines and transformers that supply them with electricity produce electrical 60-Hz noise, which may contaminate an EKG waveform.

- Fig. (a) shows a typical noise-free EKG signal and Fig. (b) shows a corresponding contaminated version.



(*a*) Noise-free EKG signal



(*b*) Contaminated EKG signal

- As can be seen, the distinct features of the EKG are all but obliterated in the contaminated signal and are, therefore, difficult, if not impossible, to discern.

  A diagnosis based on such an EKG would be unreliable.

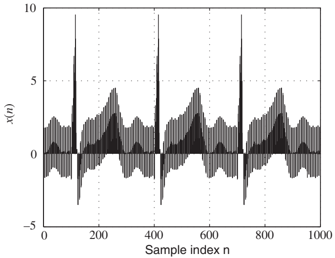
- As can be seen, the distinct features of the EKG are all but obliterated in the contaminated signal and are, therefore, difficult, if not impossible, to discern.

  A diagnosis based on such an EKG would be unreliable.

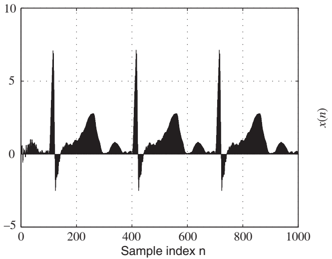
- Since electrical noise originating from the power supply has a well defined frequency, i.e., 60 Hz, one can design a bandstop filter that will reject the electrical noise.

  Such a filter has been designed using the methods to be studied in later chapters and was then used to process the contaminated EKG signal.

- Fig. (a) shows the contaminated EKG signal and Fig. (b) shows the filtered version.



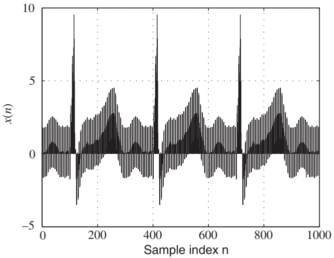
(b) Contaminated EKG signal



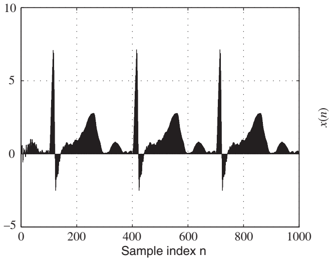
(c) Filtered contaminated EKG signal

Processing of EKG Signals *Cont'd*

- Fig. (a) shows the contaminated EKG signal and Fig. (b) shows the filtered version.
- As can be seen, the filtered signal is a faithful reproduction of the original noise-free signal, apart from some artifacts over the interval n=0 to 100 due to the transient response of the bandstop filter.

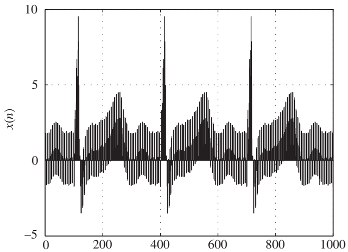


(*b*) Contaminated EKG signal

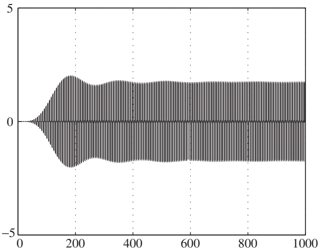


(*c*) Filtered contaminated EKG signal

- As another experiment, just to illustrate the nature of filtering, the contaminated EKG signal was passed through a bandpass filter which was designed to select the 60-Hz noise component.

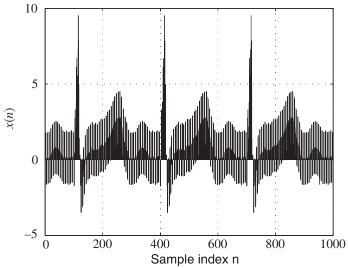


(*b*) Contaminated EKG signal

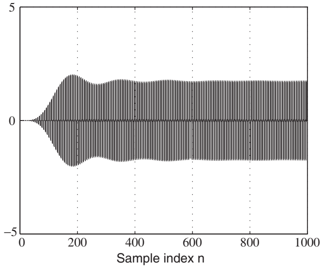


(d) Output of bandpass filter

- As another experiment, just to illustrate the nature of filtering, the contaminated EKG signal was passed through a bandpass filter which was designed to select the 60-Hz noise component.
- After an initial transience over the interval $n=0$ to 150, a steady noise component is isolated by the bandpass filter.



(b) Contaminated EKG signal



(d) Output of bandpass filter

Processing of Stock Exchange Data

- We are all interested in the health of the market place for various reasons.

  We would all like, for example, to save some money for another day and, naturally, we would prefer to invest any such funds in secure low-risk stocks, bonds, or mutual funds that provide high returns.

Processing of Stock Exchange Data

- We are all interested in the health of the market place for various reasons.

  We would all like, for example, to save some money for another day and, naturally, we would prefer to invest any such funds in secure low-risk stocks, bonds, or mutual funds that provide high returns.

- To make financial decisions such as these, we read the business section of our daily newspaper or browse the Web for numerical stock-exchange data.

Processing of Stock Exchange Data

- We are all interested in the health of the market place for various reasons.

  We would all like, for example, to save some money for another day and, naturally, we would prefer to invest any such funds in secure low-risk stocks, bonds, or mutual funds that provide high returns.

- To make financial decisions such as these, we read the business section of our daily newspaper or browse the Web for numerical stock-exchange data.
- Naturally, we would like to make investments that grow steadily from year to year at a steady rate and never devalue, but this is not what happens in real life.

  The prices of stocks change rapidly from one day to the next and once in a while, for example, when a market recession occurs, they can actually lose a large proportion of their values.

- There are many economic forces that cause the value of a stock to change.

  Some of these forces are of short duration while others reflect long-term economic pressures.

- There are many economic forces that cause the value of a stock to change.

  Some of these forces are of short duration while others reflect long-term economic pressures.

- As long-term investors, we should perhaps ignore the day-to-day variations and focus as far as possible on the underlying changes in the stock price.

Processing of Stock Exchange Data *Cont'd*

- There are many economic forces that cause the value of a stock to change.

  Some of these forces are of short duration while others reflect long-term economic pressures.

- As long-term investors, we should perhaps ignore the day-to-day variations and focus as far as possible on the underlying changes in the stock price.

- An experienced investor may be able to draw conclusions by simply comparing the available stock-exchange data of two competing stocks.

  For the rest of us this is not an easy task but through the use of DSP, the task can be greatly simplified.

- The price of a company's stock is a signal and, as such, it possesses a spectrum that can be manipulated through filtering.

- The price of a company's stock is a signal and, as such, it possesses a spectrum that can be manipulated through filtering.
- Day-to-day variations in a stock constitute the *high-frequency* part of the spectrum whereas the underlying trend of the stock is actually the *low-frequency* part.

Processing of Stock Exchange Data *Cont'd*

- The price of a company's stock is a signal and, as such, it possesses a spectrum that can be manipulated through filtering.
- Day-to-day variations in a stock constitute the *high-frequency* part of the spectrum whereas the underlying trend of the stock is actually the *low-frequency* part.
- If we are interested in the long-term behavior of a stock, then perhaps we should filter out the high-frequency part of the spectrum.

  On the other hand, if we are interested in the volatility of the stock, then we should filter out the low-frequency content.

- The price of a company's stock is a signal and, as such, it possesses a spectrum that can be manipulated through filtering.

- Day-to-day variations in a stock constitute the *high-frequency* part of the spectrum whereas the underlying trend of the stock is actually the *low-frequency* part.

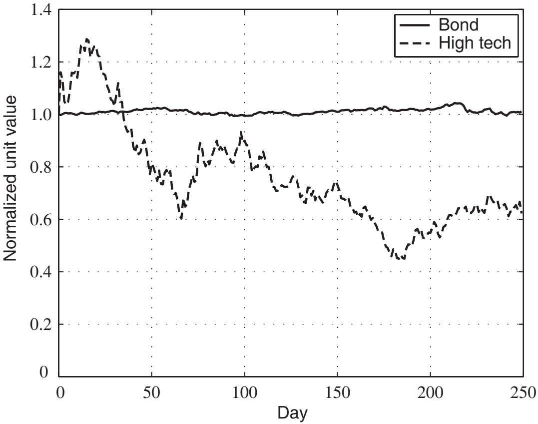
- If we are interested in the long-term behavior of a stock, then perhaps we should filter out the high-frequency part of the spectrum.

  On the other hand, if we are interested in the volatility of the stock, then we should filter out the low-frequency content.

- The high-frequency or low-frequency content of a signal can be filtered out by using a lowpass or highpass filter as appropriate.

- To illustrate these ideas, two actual mutual funds, a bond fund and a high-tech fund, were chosen at random for processing.

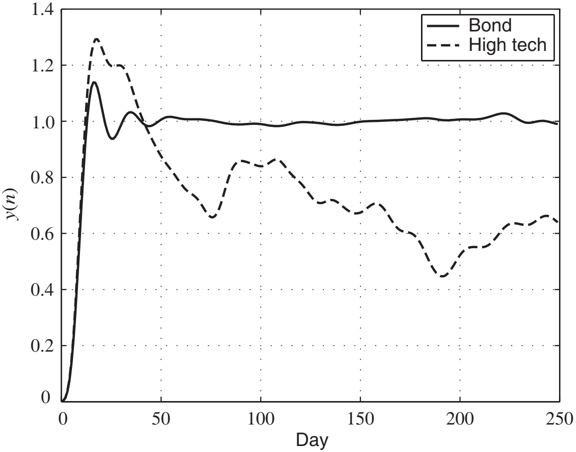
  One year's worth of data were chosen for processing pertaining to calendar year 2001 and to facilitate the comparison, the unit values of the two funds were normalized to unity at the start of the year, namely, January 1, 2001.



(a)

Note: 2001 was a bad year for high-technology stocks and mutual funds!

- Lowpass filtering produced the following results:



(b)

- The plots show certain anomalies during the first 50 or so sample values.

  These are due to the initial transience that exists in all types of systems, including filters, which will be explained later on.

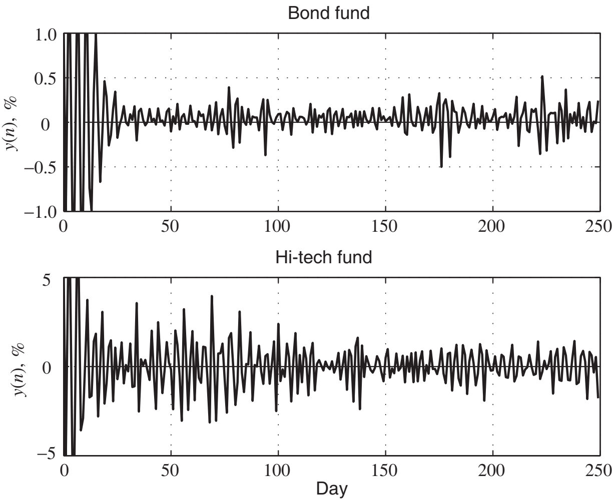
Processing of Stock Exchange Data *Cont'd*

- The plots show certain anomalies during the first 50 or so sample values.

  These are due to the initial transience that exists in all types of systems, including filters, which will be explained later on.

- Ignoring the initial transience, the plots show that the lowpass filter has removed the day-to-day variations and that makes it easier to discern the underlying trend of the fund.

- Highpass filtering produced the following results:



(c)

- The highpass filter removed the lowpass content but, like the lowpass filter, it introduced an initial transience.

- The highpass filter removed the lowpass content but, like the lowpass filter, it introduced an initial transience.

- Ignoring the initial transience and noting the difference in the y-axis scales, we observe that the amplitude of the high-frequency content in the high-tech fund is 10 times that in the bond fund.

  In effect, the high-tech fund is 10 times more volatile than the bond fund, as may be expected.

This slide concludes the presentation.
Thank you for your attention.