Design and Implementation of FIR and IIR Filters to Clean Noisy Signals Using Python

PYTHON CRT PROJECT

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1.Introduction

Background:-

In the field of digital signal processing (DSP), filters are used extensively to manipulate signals to enhance useful information and reduce noise or unwanted components. Many real-world signals—whether audio, biomedical, or sensor outputs—contain noise which can obscure important characteristics. Filtering is essential to improving signal quality for analysis or further processing.

Objective:-

This project focuses on two primary digital filter types: FIR (Finite Impulse Response) and IIR (Infinite Impulse Response). Using Python, SciPy, and Matplotlib, the goal is to design, implement, and compare these filters to clean noisy signals.

Structure:-

 Introduce theory behind FIR and IIR filters.

 Design filters using Python libraries.

 Generate noisy test signals.

 Apply filters and visualize results.

 Compare filter performance.

2.Fundamentals of Digital Filters

Discrete-Time Signals:-

Signals processed in digital systems are discrete in time, sampled at a sampling frequency fs. The Nyquist frequency fN=fs/2defines the maximum frequency representable without aliasing.

Digital Filters Overview:-

Filters process discrete samples to modify frequency components:

 Lowpass filters allow frequencies below cutoff fc.  Highpass filters allow frequencies above fc.

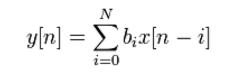
 Bandpass filters allow frequencies between two cutoffs.  Bandstop filters attenuate frequencies between two cutoffs.

Impulse Response and System Function:-

A filter’s impulse response defines how it responds to a single impulse. The system function H(z) characterizes filter behavior in the z-domain.

3. FIR Filters: Theory

FIR Filter Definition

An FIR filter has a finite number of coefficients bk: 

where N is the order of the filter.

Characteristics:-

 Non-recursive: output depends only on input.  Always stable.

 Can have exactly linear phase.

 Typically higher order needed for sharp transitions.

Design Using Window Method:-

The ideal lowpass filter impulse response is truncated using a window function (e.g., Hamming window) to limit length and reduce sidelobes.

4: IIR Filters: Theory

IIR Filter Definition:-

An IIR filter uses both inputs and previous outputs: 

Characteristics:-

 Recursive filter; output feedback.

 Can achieve sharper cutoff with fewer coefficients.  Stability depends on pole locations.

 Phase response is typically nonlinear.

Butterworth Filter:-

A Butterworth filter is maximally flat in the passband and has monotonic magnitude response, commonly used for general purpose lowpass filtering.

5: Problem Statement and Objectives

Problem Statement

Noisy signals complicate analysis and reduce system performance. The goal is to remove noise effectively without distorting signal features.

Objectives

 Generate noisy test signals with known frequencies.  Design FIR and IIR lowpass filters using Python.  Apply filters to noisy signals.

 Plot signals and filter frequency responses.

 Compare filter performance.

6: Software and Libraries

Python 3.x:-

The project is implemented in Python for its extensive scientific ecosystem.

Libraries:-

 NumPy: Efficient numerical computations and array handling.

 SciPy.signal: Signal processing functions including filter design and application.

 Matplotlib: Visualization of time series and frequency responses.

Installation:-

pip install numpy scipy matplotlib

7: Signal Generation and Noise Model

Clean Signal:-

We create a clean sine wave:

x(t)= sin(2πft)

with frequency f=5Hz.

Noise Model:-

Additive Gaussian noise and sinusoidal interference at 50 Hz are added

where noise is white Gaussian noise.

8: FIR Filter Design in Python Design Parameters:-

 Filter order

 Cutoff frequency fc=10 Hz.

 Sampling frequency fs=500 Hz.

Design Code:-

from scipy.signal import firwin

nyq = 0.5 \* fs

normalized\_cutoff = cutoff / nyq

fir\_coeff = firwin(numtaps=order+1, cutoff=normalized\_cutoff,

pass\_zero='lowpass')

Explanation:-

 numtaps is filter length = order + 1.

 pass\_zero='lowpass' designs a lowpass filter.

9: IIR Filter Design in Python

Butterworth Design:-

from scipy.signal import butter

b, a = butter(N=order,

Wn=normalized\_cutoff, btype='low')

 N is filter order.

 Wn is normalized cutoff.

 btype='low' for lowpass.

10: Applying Filters

FIR Filtering:-

from scipy.signal import lfilter

filtered\_fir = lfilter(fir\_coeff, 1.0, noisy\_signal)

IIR Filtering:-

Use zero-phase filtering to avoid phase distortion: from scipy.signal import filtfilt

filtered\_iir = filtfilt(b, a, noisy\_signal)

11: Frequency Response

FIR Filter:-

from scipy.signal import freqz

w, h = freqz(fir\_coeff)

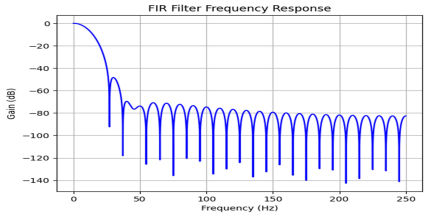
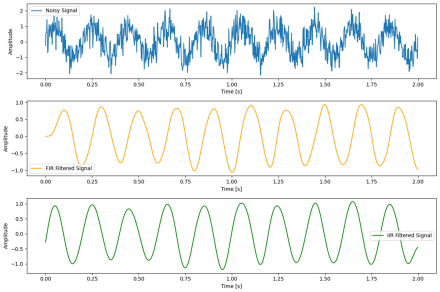
plt.plot(w \* fs / (2\*np.pi), 20 \* np.log10(abs(h)))

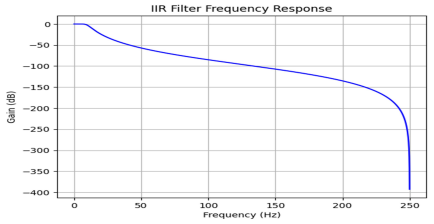
IIR Filter:-

Same method with numerator and denominator coefficients.

12: Visualization of Signals

noisy signal,FIR filtered and IIR filtered signals in time domain to visually assess noise reduction.





13: Performance Comparison Goal:-

Effectively suppress undesired components such as high frequency noise (e.g., 50 Hz interference) while preserving the desired signal (5 Hz sine wave).

FIR Filter:

 Strengths: Offers strong attenuation of frequencies above the cutoff, especially with higher filter orders.

 Observed Performance: The FIR filter successfully removed high-frequency noise, showing a smooth waveform in the filtered signal.

 Limitation: Requires a higher order to achieve a sharp cutoff, especially for narrow transition bands.

IIR Filter:

 Strengths: Achieves sharp roll-off near the cutoff frequency with relatively lower order.

 Observed Performance: The IIR filter effectively eliminated the 50 Hz interference with fewer coefficients.  Trade-off: More susceptible to ripple or gain irregularities near the cutoff band.

Verdict: Both filters attenuate noise well; IIR does it more efficiently (lower order), but FIR does so more predictably.

14: Applications

Filtering is vital in:-

 Audio denoising.

 Biomedical signal cleanup (ECG, EEG).

 Communications.

 Sensor data processing.

15: Extending the Project Ideas include:

 Designing bandpass and highpass filters.  Adaptive filtering techniques.

 Real-time filtering.

 Multirate filtering.

16: Challenges

 Choosing filter parameters.

 Managing phase distortion.

 Balancing order vs complexity.

 Noise modeling accuracy.

17: Full Python Code Listing

import numpy as np

import matplotlib.pyplot as plt

from scipy.signal import firwin, lfilter, freqz, butter, filtfilt

def design\_fir\_filter(order, cutoff, fs, filter\_type='low'):

nyq = 0.5 \* fs

normalized\_cutoff = np.array(cutoff) / nyq

if filter\_type == 'low':

pass\_zero = True

elif filter\_type == 'high':

pass\_zero = False

elif filter\_type in ['bandpass', 'bandstop']:

pass\_zero = filter\_type

else:

raise ValueError("Invalid filter\_type. Choose from 'low', 'high', 'bandpass', 'bandstop'.")

fir\_coeff = firwin(order + 1, normalized\_cutoff, pass\_zero=pass\_zero) return fir\_coeff

def design\_iir\_filter(order, cutoff, fs, filter\_type='low'):

nyq = 0.5 \* fs

normalized\_cutoff = np.array(cutoff) / nyq

b, a = butter(order, normalized\_cutoff, btype=filter\_type, analog=False) return b, a

def apply\_filter(b, a, signal, use\_filtfilt=False):

if use\_filtfilt:

filtered\_signal = filtfilt(b, a, signal) # zero-phase filtering

else:

filtered\_signal = lfilter(b, a, signal)

return filtered\_signal

def plot\_frequency\_response(b, a=1, fs=1.0, title='Frequency Response'): w, h = freqz(b, a, worN=8000)

plt.plot((fs \* 0.5 / np.pi) \* w, 20 \* np.log10(abs(h)), 'b') plt.title(title)

plt.xlabel('Frequency (Hz)')

plt.ylabel('Gain (dB)')

plt.grid(True)

plt.show()

if \_\_name\_\_ == "\_\_main\_\_":

fs = 500.0 # Sampling frequency (Hz)

t = np.arange(0, 2.0, 1/fs) # Time vector for 2 seconds

# Create a noisy signal: 5 Hz sine + white noise + 50 Hz interference freq\_signal = 5.0

noisy\_signal = (

np.sin(2 \* np.pi \* freq\_signal \* t) +

0.5 \* np.random.randn(len(t)) +

0.3 \* np.sin(2 \* np.pi \* 50 \* t)

)

# Filter parameters

fir\_order = 50

iir\_order = 4

cutoff = 10 # cutoff frequency (Hz)

filter\_type = 'low' # lowpass filter

# Design FIR filter

fir\_b = design\_fir\_filter(fir\_order, cutoff, fs, filter\_type) # Design IIR filter

iir\_b, iir\_a = design\_iir\_filter(iir\_order, cutoff, fs, filter\_type)

# Apply filters

fir\_filtered = lfilter(fir\_b, [1.0], noisy\_signal)

iir\_filtered = apply\_filter(iir\_b, iir\_a, noisy\_signal, use\_filtfilt=True)

# Plot time domain signals

plt.figure(figsize=(12, 8))

plt.subplot(3, 1, 1)

plt.plot(t, noisy\_signal, label='Noisy Signal')

plt.legend()

plt.xlabel('Time [s]')

plt.ylabel('Amplitude')

plt.subplot(3, 1, 2)

plt.plot(t, fir\_filtered, label='FIR Filtered Signal', color='orange') plt.legend()

plt.xlabel('Time [s]')

plt.ylabel('Amplitude')

plt.subplot(3, 1, 3)

plt.plot(t, iir\_filtered, label='IIR Filtered Signal', color='green') plt.legend()

plt.xlabel('Time [s]')

plt.ylabel('Amplitude')

plt.tight\_layout()

plt.show()

# Plot frequency responses

plot\_frequency\_response(fir\_b, fs=fs, title='FIR Filter Frequency Response') plot\_frequency\_response(iir\_b, iir\_a, fs=fs, title='IIR Filter Frequency Response'

18: Experimental Results

 Filter effectiveness.

 Frequency response plots.

 Signal waveforms.

19: Conclusions

Summary of findings: FIR filters provide stable linear phase response; IIR filters are efficient but phase nonlinear. Both can effectively clean noisy signals when properly designed.