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

PYTHON CRT PROJECT

EEE-B/SECTION

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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 f_s. The Nyquist frequency $f_N=f_s/2$defines the maximum frequency representable without aliasing.

Digital Filters Overview:-

Filters process discrete samples to modify frequency components:

- **Lowpass filters** allow frequencies below cutoff f_c.
- **Highpass filters** allow frequencies above f_c.
- **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 b_k:

$$y[n] = \sum_{i=0}^{N} b_i x[n-i]$$

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:

$$y[n] = \sum_{l=1}^{N} a_l y[n-l] + \sum_{k=0}^{M} b_k x[n-k]$$

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:

$x(t) = \sin(2\pi f t)$

with frequency $f = 5_{Hz}$.

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:-

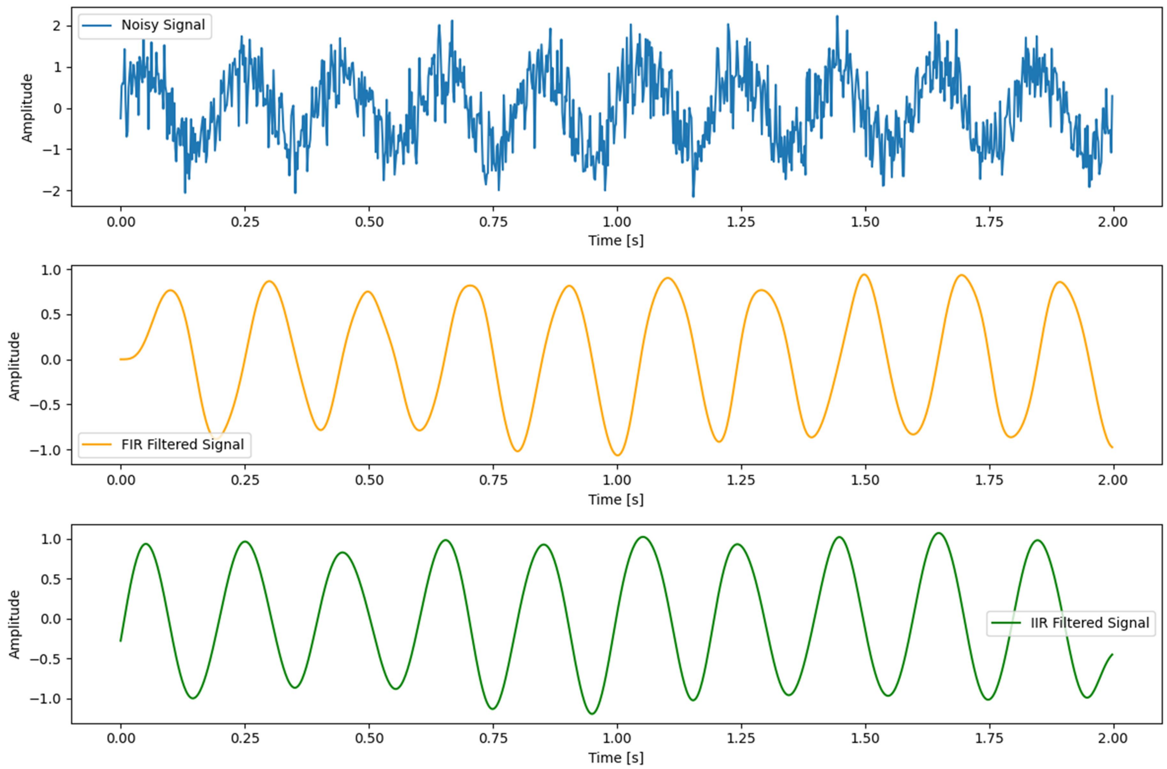
```
from scipy.signal import freqz

w, h = freqz(fir_coeff)
plt.plot(w * fs / (2*np.pi), 20 *
np.log10(abs(h)))
```

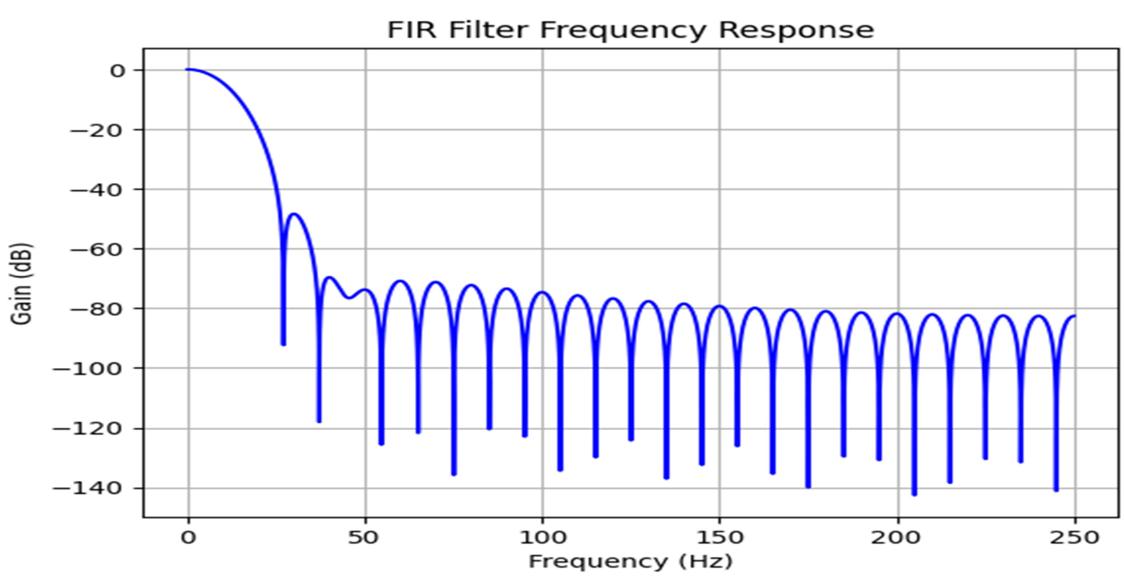
IIR Filter:-

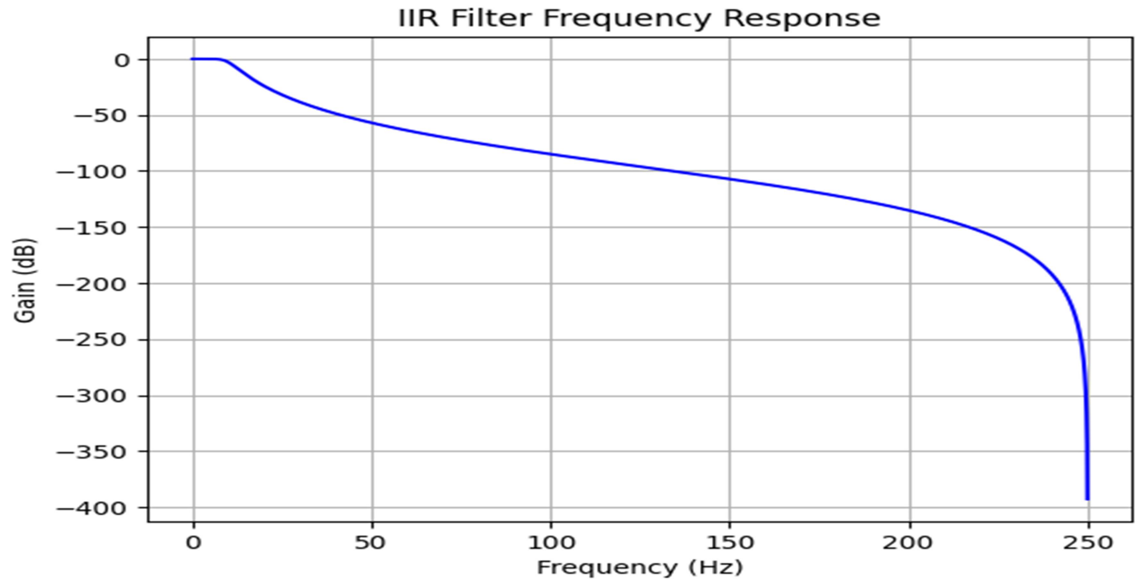
Same method with numerator and denominator coefficients.

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.