DE GRUYTER OPEN

STUDIES IN LOGIC, GRAMMAR AND RHETORIC 47 (60) 2016
DOI: 10.1515/slgr-2016-0049

Early-Stage Pilot Study on Using Fractional-Order Calculus-Based Filtering for the Purpose of Analysis of Electroencephalography Signals

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Abstract. Analysis of Electroencephalography (EEG) signals has recently awoken the increased interest of numerous researchers all around the world with regard to rapid development of Brain-Computer Interaction-related research areas and because EEG signals are implemented in most of the non-invasive BCI systems, as they provide necessary information regarding activity of the brain. In this paper, a very early stage pilot study on implementation of filtering based on fractional-order calculus (Bi-Fractional Filters – BFF) for the purpose of EEG signal classification is presented in brief.

Introduction

Due to the recent rapidly and dynamically growing development of non-invasive Brain-Computer Interface systems, the analysis of Electroencephalography (EEG) signals has become one of the main research interests of numerous scientific groups all around the world (Dalir et al., 2010; Magin, 2006; Tenreiro Machado, 2011). Such situation resulted from the fact that EEG signals can be successfully applied in most of the BCI systems, as they are able to provide all the necessary information about the brain's activity (Kawala-Janik et al., 2014, 2015).

The application of EEG signals in BCI, especially from cost-effective sensors, is a difficult task, as it relies on real-time analysis and interpretation of low quality data. In addition, interpretation depends on the applied method of signal processing (Kawala-Janik et al., 2015). Although the theory behind using fractional calculus in technical application had already been developed in the 19th century, this concept has only become popular in recent years. One rapidly developing area is implementation of fractional filters for bio-signals processing, as it allows great flexibility in filter shaping (Radwan et al., 2009; Wang et al., 2015). It is also because the theory of such filters is relatively well grounded, although some implementation-related problems are still open (Kawala-Janik et al., 2015).

Fractional-order methods-based systems are applied in order to enable the detection of waves in biomedical signals or to model them. This is because they are an excellent source for noise removal or enhancing crucial information in signals where (e.g. EEG) the amplitude is low (Ferdi, 2011).

In this paper, a pilot study on implementation of simple non-integer order filtering (Bi-Fractional Filters – BFF) for the purpose of EEG signal classification is briefly presented. The paper also contains some basic information regarding non-integer filtering.

Non-Integer Order Filtering

While implementing the fractional-order calculus method, it is important to note that both the derivative and integral of a function is generalized to arbitrary orders. These mathematical methods have found broad usage in analysis of biomedical signals and images (Benitez et al., 2016; Ferdi, 2011). Implementation of a fractional-order subsystem on a hardware platform is currently a broadly researched topic and, therefore, one of the main aims is the design of an appropriate algorithm for realization of non-integer order elements and their approximation, in order to allow for discrete implementation (Bania et al., 2013; Dalir et al., 2010; Petras, 2011). The most important aspects of the applied theory with regard to fractional-order calculus methods can be found in texts by Podlubny (1999) and Baranowski et al. (2015), among others. The Oustaloup method was described in more detail in Oustaloup et al. (2000). It is also important to note that fractional-order filtering is becoming more and more popular in the analysis of various biomedical signals, such as ECG or EEG signals (Bauer et al., 2016; Wang et al., 2015). The reason for that is the fact that using fractional-order filters provides much compromise between the retention of the information contained by the analysis signal and noise reduction in it, compared to traditional filtering methods (Sheng et al., 2011; Wang et al., 2015).

The typical approach to fractional-order filtering consists of both analogue design and implementation, where the digital realization of such system is susceptible to problems such as infinite memory requirement and sensitivity to numerical errors, which plays a crucial role in analysis of sensitive data such as EEG signals (Baranowski et al., 2014b; Ferdi, 2011). For this paper, the fractional filtering process was carried out with the implementation of the Laguerre impulse response approximation (Baranowski et al., 2014a). Fractional-order differentiators and integrators contain very interesting features, which could be successfully applied for the purpose of design of digital filters – later applied for analysis of biomedical data (Ferdi, 2011).

Apart from the Oustaloup-based methods (Oustaloup, 2000), the one based on Grunwald-Letnikov also provides some promising results (Dalir et al., 2010; Wang et al., 2015).

Methodology and Results

It is a very challenging task to localize the spectra of biomedical signals – due to their variability. Therefore, the implementation of fractional-order calculus-based filtering methods may be a very good alternative to the traditional filters applied for that purpose (Ferdi, 2011).

In this paper, the authors have decided to focus on efficient methods for using fractional-order filtering that do not carry with them the burden of infinite memory. The problem of approximating the non-integer order system with an integer order has been analyzed for many years and the most popular approaches are based on Oustaloup transfer function approximation. However, the problem with using the Oustaloup method is that it is very sensitive to high discretization frequencies and rounding errors and can become unstable easily (Baranowski et al., 2016).

The main focus was put on the digital realization of the bi-fractional filters (BFF), which can be given by the below transfer function:

$$G(s) = \frac{c}{s^{2\alpha} + 2bs^{\alpha} + c} \tag{1}$$

where:

- α is base order,
- b is damping coefficient,
- c is free coefficient.

It is possible to represent the (1) in form of a differential equation system with zero initial conditions, as below:

$$
\begin{aligned}
{}_0^C D_t^{\alpha} \mathbf{x}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}u \\
y(t) &= \mathbf{C}\mathbf{x}(t)
\end{aligned}
\tag{2}
$$

with the below matrix:

$$
\mathbf{A} = \begin{bmatrix} 0 & 1 \\ -c & -2b \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} c & 0 \end{bmatrix}
\tag{3}
$$

Where $x(t)$ is state space of filter, $u(t)$ is input signal value in time and $y(t)$ is output of the filtered signal. In Figure 1, a simplified diagram of filtering realization is presented.

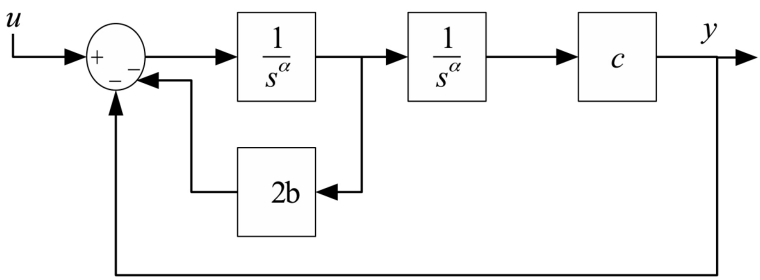

Figure 1. Bi-Fractional Filter realization scheme

For the purpose of this work, the data was collected from the Emotive EPOC headset, which is not a typical piece of medical equipment, but a gaming headset (Kawala-Janik et al., 2015; Kline et al., 2015). The choice for the application of Emotiv EPOC for the purpose of data gathering resulted from the fact that it is a reliable tool for data collection (Benitez et al., 2016; Kline et al., 2015), which can be used anywhere due to its features (Badcock et al., 2013). The sampling frequency was only 128 Hz (Kawala-Janik et al., 2015). It is important to mention that the obtained data is not "raw". The analyzed frequency was 8–12 [Hz] ("mu"-waves) (Kawala-Janik et al., 2015). The data collected for research purposes was from 15 healthy, right-handed male subjects. Subjects had to perform imagery right- and left-hand movement in accordance with instructions appearing on screen. The data was collected for the purpose of supporting doctoral work (partially). Some of the information regarding the tested group can be found in Kawala-Janik (2013).

Figure 2 illustrates the time series of the analyzed "mu"-waves recorded from the right hemisphere of the brain (C3).

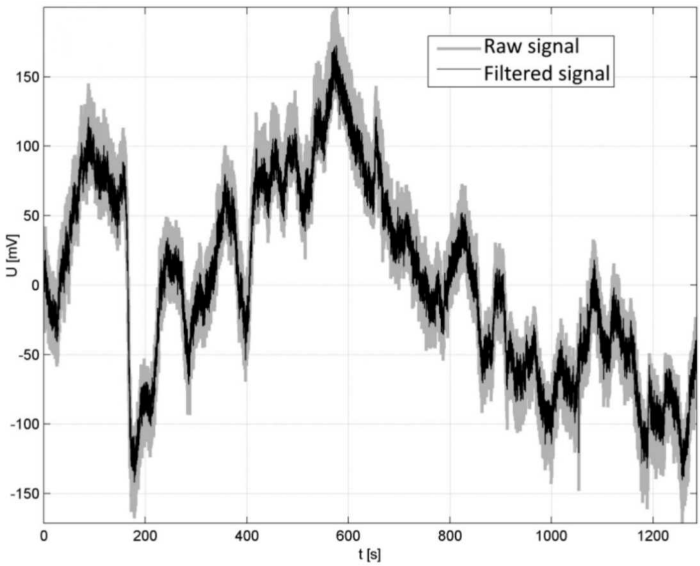

Figure 2. Time series in the C3 point (sample 1)

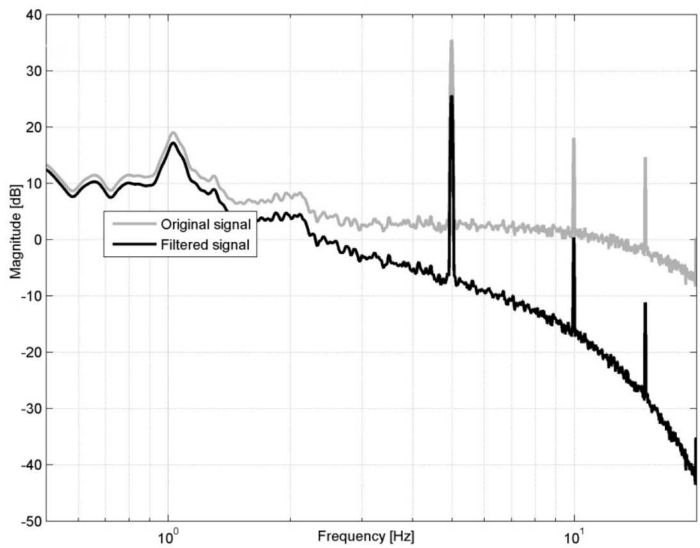

Figure 3. Spectral analysis in the C3 point (sample 1)

Figure 3 illustrates spectral analysis of the same signal (sample 1) as in Figure 2. It is possible to observe the damping of 28 dB/dec, which is not possible while using traditional filters (for further details please see: Baranowski et al., 2014a, 2014b; Piatek et al., 2014).

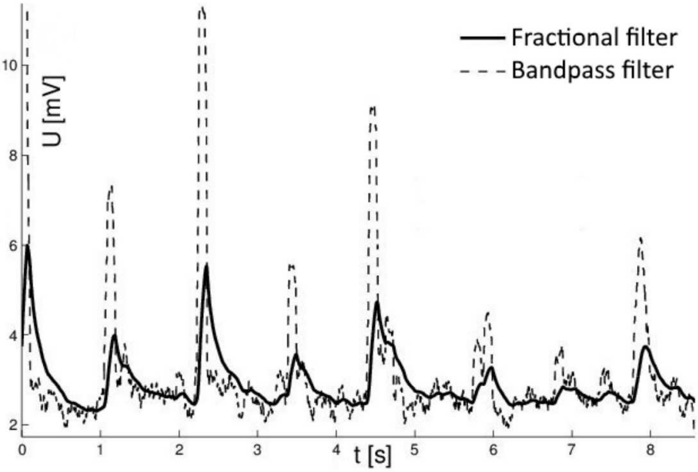

Figure 4. Fractional and band-pass filtering of the analyzed point (sample 2)

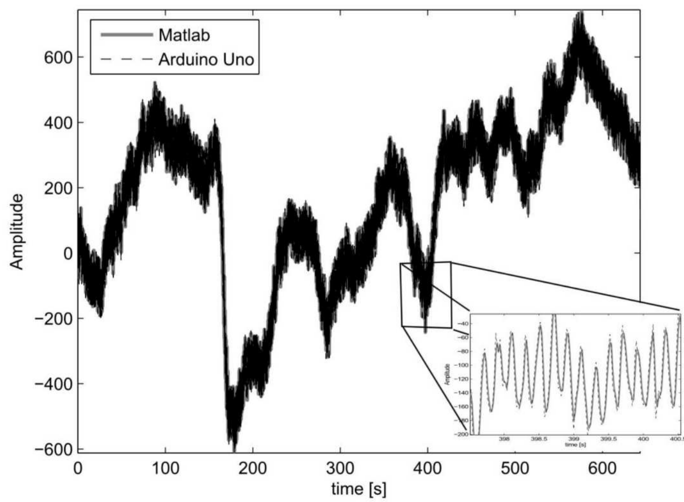

Figure 5. Filtering result comparison of the implementation of the Oustaloup time-domain approximation and Matlab-Simulink for $\alpha = 0.7$

In Figure 4, the comparison of using two types of filtering – a basic band-pass (8 and 12 Hz) filter and a fractional BFF filter (with the given parameters: $\alpha = 0.7$, $b = 11.1688$, $c = 124.7412$) – is presented. The BFF filter parameters were chosen in accordance with details shared by Baranowski et al. (2014a) and Piatek et al. (2014). In Figure 5, comparison of Oustaloup time-domain approximation and Matlab-Simulink is illustrated.

Conclusions

The research described in this paper is currently in the very initial study stage and the idea of using BFF filtering is being tested. The results are promising and show a wide range of filter design possibilities. Implementation of such filtering in fractional form is numerically impossible. As such, approximation has to be taken into account due to occurrence of numerical errors. The high order of approximation enables more accurate filter response, but it may provide less numerical stability. The implementation of BFF Filtering is not very popular yet, but the authors assume that it will become widely used in the near future due to its efficiency and wider potential in development of frequency filter characteristics. The proposed method also offers more flexible adjustment of frequency characteristics (Baranowski et al., 2016). The previous applied methods have also been presented in studies conducted by Kawala-Janik et al. (2014, 2015) in more detail.

Acknowledgments

This work was partially realized in the scope of the project "Design and application of non-integer order subsystems in control systems" – National Science Centre (PL) – DEC-2013/09/D/ST7/03960.

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