A Mixed Filtering Approach for Real-Time Seizure State Tracking Using Multi-Channel Electroencephalography Data

Alexander G. Steele, *Graduate Student Member, IEEE*, Sankalp Parekh, Hamid Fekri Azgomi, Mohammad Badri Ahmadi, Alexander Craik, *Graduate Student Member, IEEE*, Sandipan Pati, Joseph T. Francis, Jose L. Contreras-Vidal, *Fellow, IEEE*, and Rose T. Faghih, *Member, IEEE*

***Abstract*—Real-time continuous tracking of seizure state is necessary to develop feedback neuromodulation therapy that can prevent or terminate a seizure early. Due to its high temporal resolution, high scalp coverage, and non-invasive applicability, electroencephalography (EEG) is a good candidate for seizure tracking. In this research, we make multiple seizure state estimations using a mixed-filter and multiple channels found over the entire sensor space; then by applying a Kalman filter, we produce a single seizure state estimation made up of these individual estimations. Using a modified wrapper feature selection, we determine two optimal features of mixed data type, one continuous and one binary analyzing all available channels. These features are used in a state-space framework to model the continuous hidden seizure state. Expectation maximization is performed offline on the training and validation data sets to estimate unknown parameters. The seizure state estimation process is performed for multiple channels, and the seizure state estimation is derived using a square-root Kalman filter. A second expectation maximization step is utilized to estimate the unknown square-root Kalman filter parameters. This method is tested in a real-time applicable way for seizure state estimation. Applying this approach, we obtain a single seizure state estimation with quantitative information about the likelihood of a seizure occurring, which we call seizure probability. Our results on the experimental data (CHB-MIT EEG database) validate the proposed estimation method and we achieve an average accuracy, sensitivity, and specificity of 92.7%, 92.8%, and 93.4%, respectively. The potential applications of this seizure estimation model are for closed-loop neuromodulation and long-term quantitative analysis of seizure treatment efficacy.**

***Index Terms*—Electroencephalography (EEG), epilepsy, Kalman filter, neurofeedback, real-time detection, state estimation, state-space methods.**

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This work involved use of existing publicly available human subject data, and the information was recorded so subjects cannot be identified. Hence, this human subject data is exempt from review board approval.

Alexander G. Steele, Jose L. Contreras-Vidal, and Rose T. Faghih are with the Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004 USA, and also with the NSF IUCRC BRAIN Center, University of Houston, Houston, TX 77004 USA (e-mail: agsteele@uh.edu; jlcontreras-vidal@uh.edu; rtfaghih@uh.edu).

Sankalp Parekh, Hamid Fekri Azgomi, and Alexander Craik are with the Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004 USA (e-mail: sparekh2@uh.edu; hfekriazgomi@uh.edu; arcraik@uh.edu).

Mohammad Badri Ahmadi is with the Department of Biomedical Engineering, University of Houston, Houston, TX 77004 USA (e-mail: mbadri-ahmadi@uh.edu).

Sandipan Pati is with the Department of Neurology, McGovern Medical School, The University of Texas Health Science Center at Houston, Houston, TX 77030 USA (e-mail: sandipan.pati@uth.tmc.edu).

Joseph T. Francis is with the Department of Biomedical Engineering and the Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004 USA (e-mail: jtfranci@uh.edu).

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I. Introduction

APPROXIMATELY 50 million people live with epilepsy worldwide [2]. In the US alone, the National Institutes of Health spends over $150 million each year on epilepsy research. This accounts for roughly 82% of research that is not coming from industry sources [3]. Epilepsy is a neurological disorder which can occur at any age, currently has no cure, and is characterized by seizures that can happen without noticeable warning [3]. This can lead to other health problems such as brain injury from falling, psychiatric conditions, and a reduction in quality of life [4], [5]. It is a spectrum with a wide range of seizure types, which vary from person-to-person [6], [7]. For example, a focal seizure is one that is triggered by a localized portion of the brain, while a general seizure can be triggered in multiple parts of the brain [7].

Treatments for epilepsy currently focus on anti-epileptic medications [8]. While most patients find that their symptoms are well controlled with a drug regimen, more than 90% still experience seizures [8], [9]. These medications also

state as they evolve and progress is clinically relevant as they may assist in developing feedback therapy (adaptive neuromodulation) [28], [29]. In this study, we define the likelihood of a seizure occurring as seizure probability. One practical