An IoT-based Drug Delivery System for Refractory Epilepsy

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***Abstract*—Epilepsy affects approximately 1% of the worlds population and is medically refractory in a large fraction of these patients necessitating innovative solutions for seizure control. Here, we describe a unified drug delivery system within the IoT framework which provides drug injection upon seizure detection for seizure control. An electromagnetically actuated valveless micropump, with a diaphragm composed of Polydimethylsiloxane (PDMS), was used for drug delivery. A prototype of the solution was implemented using Simulink® and ThingSpeak™. Simulation results demonstrate that the proposed system reduces power consumption considerably (10-30%) while maintaining high accuracy.**

***Index Terms*—IoT, Electroencephalogram (EEG), Epilepsy, Seizure Detection, Electromagnetic Actuation, Drug Delivery System, Seizure Control**

I. Introduction

Epilepsy is a neurological disorder characterized by recurrent seizures. A seizure consists of abnormal activity within the brain, which may result in loss of consciousness or convulsions [1]. Approximately 1% of the worlds population suffers from epilepsy. Seizures can be controlled through anti-epileptic drugs (AEDs) and surgery. However, approximately a third of epilepsy patients do not respond to AEDs and epilepsy surgery is suitable for a very small fraction of epilepsy patients [2]. Hence, an alternative approach which can provide an effective solution for controlling seizures is necessary [3],[4].

Our proposed drug delivery system can detect a seizure and inject an AED in a targeted area of the brain. This responsive and localized injection enhances the efficacy of the drug and provides an effective solution for epilepsy. Universal connectivity of the solution with other healthcare devices can be attained via the IoT. The IoT enables remote health monitoring and analysis of health behavior [5]. In this paper, a responsive drug delivery system (DDS) is proposed which can inject drugs into the epileptogenic zone upon seizure detection. Fig. 1 shows a block diagram of the proposed drug delivery system.

This paper is organized as follows: we discuss the novel contributions of this paper in section II. Section III briefly reviews related previous research. Section IV illustrates the drug delivery system. Section V discusses the implementation and validation of the proposed system. The paper concludes in section VI with a summary and suggestions for further research.

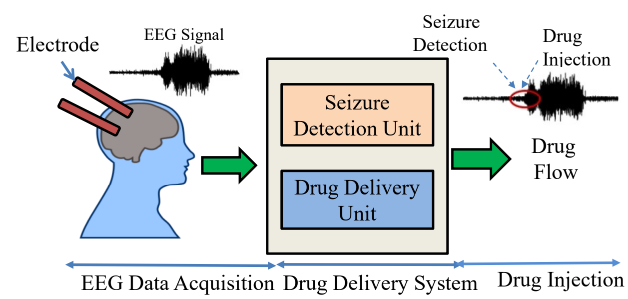

Fig. 1: Block Diagram of the Drug Delivery System (DDS).

II. Novel Contributions of This Paper

In this paper, a responsive drug delivery system (DDS) is proposed in the IoT framework which provides better detection accuracy and simultaneous drug injection. The novel contributions of this research are:

1) Discrete Wavelet Transform (DWT) based provides a conjoint time and frequency determination which is highly effective for capturing complex EEG dynamics, and leads to improved accuracy for seizure detection in comparison to existing methods.
2) Both piezoelectric and electrostatic actuation operate at a high voltage while electromagnetic actuation requires a lower actuation voltage for a desired membrane displacement. This allows a reduction in power consumption and allows its use for low power medical applications.
3) The system features better detection accuracy, lower power consumption and universal connectivity. Patient data and system performance can be accessed and analyzed remotely. Remote health monitoring of epilepsy

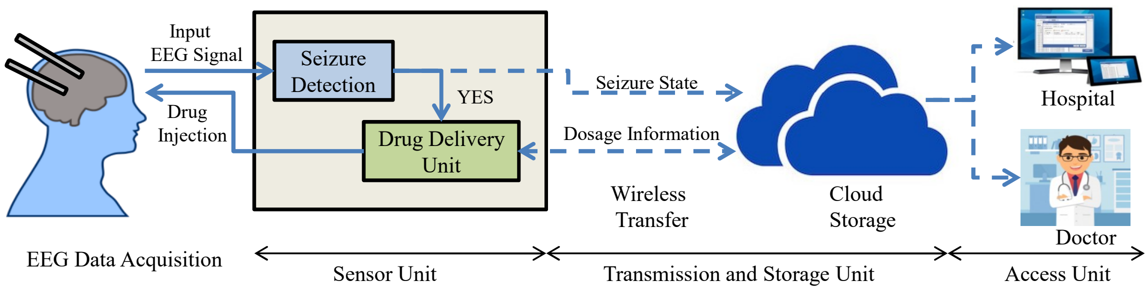

Fig. 2: Proposed System in the Internet of Medical Things (IoMT).

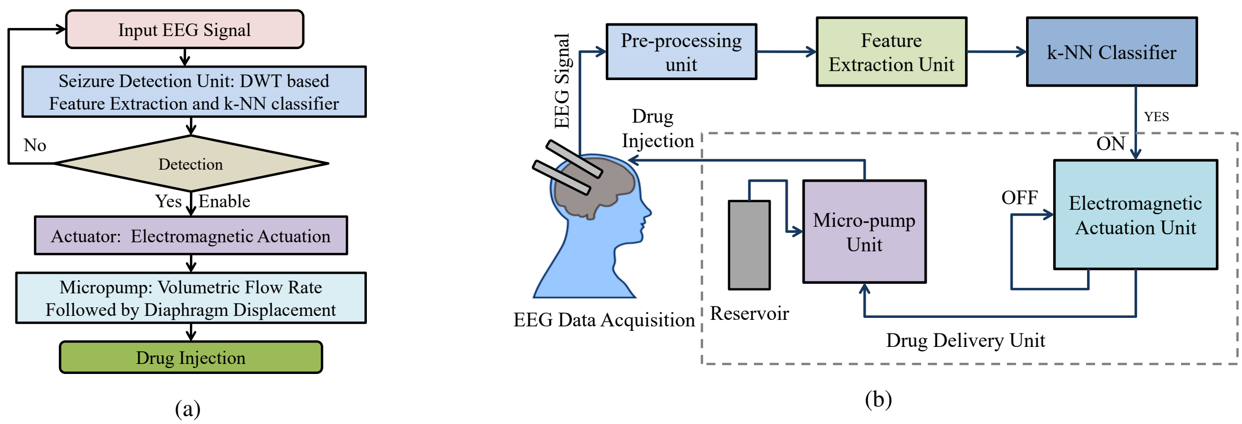

Fig. 3: Proposed Drug Delivery System (a) Flowchart (b) Architecture.

patients is facilitated by the proposed IoT framework allowing a considerable enhancement of the quality of life of epilepsy patients.

III. Related Previous Research

Seizure detection, prediction and control are active ongoing areas of research [6], [7]. Several interventional device based methods have been proposed for the control of seizures using electrical stimulation [8], focal cooling, or drug delivery [9]. A number of patients do not respond to electrical stimulation, suggesting the need for an alternative approach. Focal drug delivery has shown promising results for the suppression of seizures. An electrophoretic drug delivery device [10], which works based on the principle of organic electron ion chip (OEIP), has been proposed for on-demand drug delivery into a localized brain area. A custom hardware device [11] has been proposed to control seizures by injecting an AED directly into a specified brain area. An electromagnetic based micropump [12], [13] has been presented for a responsive drug delivery system, which consumes low power compared to piezoelectric based micropumps, while maintaining accuracy. A seizure detecting smartwatch [14], which was recently approved in the USA, can detect seizures as well as notify physicians of its occurrence. This product has proven useful for detection of convulsive seizures, but seizure suppression at onset remains an issue. The proposed drug delivery system would help to overcome these challenges and will enhance smart healthcare considerably.

IV. The Proposed Drug Delivery System

EEG Signals are initially decomposed using the DWT. Statistical features are extracted from the decomposed EEG and submitted to a k-NN classifier for detection. When a seizure is detected, AEDs are injected into the onset area to stop the seizure propagation. The IoT framework performs remote monitoring of the performance of the solution as well as drug injection upon seizure detection. Fig. 2 shows the proposed drug delivery system in the IoT framework. The flowchart and architecture of the proposed system are shown in Fig. 3.

A. *The Proposed Seizure Detection Subsystem*

The seizure detection unit (Fig. 4) consists of the following sub-units: DWT, feature extraction, and k-NN classifier. The DWT decomposes the EEG signals and provides time-frequency (TF) localization. Statistical features are extracted from each sub-band, which are then provided to the k-NN classifier for classification.

1) Statistical feature extraction from DWT: The DWT offers the advantage of TF localization, which is useful for analyzing the complex and non-stationary EEG signals. The decomposition is performed using a filter bank. The following sub-band frequencies were employed: A4 (0-5.43Hz), D4

(5.43-10.85Hz), D3 (10.85-21.7Hz), D2 (21.7-43.4Hz) and D1 (43.4-86.8Hz). The following statistical features were used: variance, standard deviation, and energy.

2) k-NN classifier: The k-NN classifier was used in two phases: training and testing. A distinct EEG dataset was used for the training and testing phases. The classification was performed using a majority vote among neighbors. A Euclidean distance metric was used to calculate the nearness of the data [7].

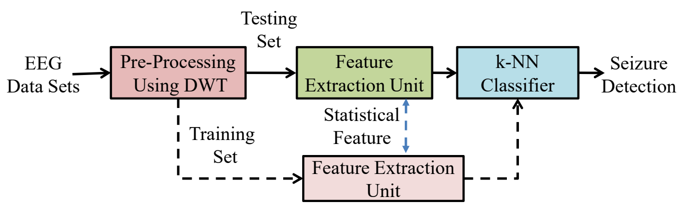

Fig. 4: Architecture of the Proposed Seizure Detection Unit.

B. Drug Delivery Subsystem

The drug-delivery subsystem micropump is shown in Fig. 5. An electromagnetic actuated valveless micropump (EAVM) offers following advantages over the other micropumps: (1) Electromagnetic actuation requires lower actuation voltage compared to other actuation mechanisms. (2) Electromagnetic actuation leads to higher deflection, faster response, and higher actuation force compared to other mechanisms. (3) Elimination of the valves makes the EAVM more reliable and simplified in structure .

When a voltage is applied to the coil a magnetic field is generated, which produces an electromagnetic force (EMF). The EMF drives the membrane in the upward and downward directions periodically and changes the volume of the pump chamber. The volumetric flow rate is a function of membrane deflection: the larger the deflection, the larger the stroke volume. The electromagnetic force between a coil and permanent magnet is given by [15]:

$$F_z = B_r \int_{t_m} A_m \frac{\delta H_z}{\delta z} dz, \tag{1}$$

where H_z is the vertical magnetic field from the coil and B_r is the remanence of the magnet. A_m and t_m denote the surface area and thickness of the magnet. The maximum diaphragm deflection can be calculated by [16]:

$$W_{max} = \frac{Fd^2}{256\pi D}, \tag{2}$$

where F is the force acting on the membrane, d is the diameter of the diaphragm, and D is the flexural rigidity of the diaphragm. $D = Eh^3/12(1-v^2)$, where E is the elastic modulus, v is Poisson's ratio, and h is the thickness of the diaphragm. The volume flow rate is [17]:

$$Q = 2\Delta V f \frac{(\eta^{1/2}-1)}{(\eta^{1/2}-1)}, \tag{3}$$

where f is the pump frequency, ΔV is the volume per stroke and η is the stroke efficiency.

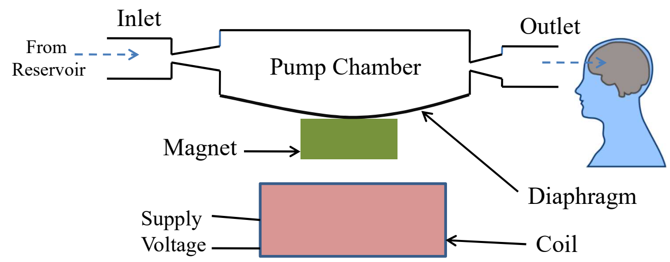

Fig. 5: Electromagnetic Actuated Valveless Micropump (EAVM).

V. Implementation and Validation of The Proposed System

The system was implemented in Simulink®. EEG signals were processed and decomposed using DWT and submitted to the feature extraction unit. The extracted features were then applied to the k-NN classifier for the detection of seizure. EEG datasets were taken from open source databases [18]. The k-NN classifier was trained using 85% of each dataset, while 15% of each dataset was used for testing. In the classification phase, a testing point is given to the classifier for the detection of seizure. The proposed approach provides 98.65% classification accuracy for normal and interictal vs. ictal EEG.

Upon seizure detection, the drug delivery unit becomes active and the coil acts as an electromagnet. The generated EMF was computed from the properties of coil, permanent magnet, and supply voltage. The desired diaphragm deflection was calculated from the diaphragm geometry and EMF. The volumetric flow rate was obtained using the actuation frequency, nozzle parameters, and other operating conditions. The IoT implementations were performed using ThingSpeak™ [19], which is an open data platform for IoT applications.

TABLE I: Characterization of Micropump

Parameters	Value	Units
Supply voltage	5	Volts
Frequency	130	Hz
Coil turn	100	
Distance between coil and magnet	1.5	mm
Pump chamber diameter	4	mm
Thickness of the membrane/diaphragm	80	μm
Elastic modulus (PDMS)	750	Kpa
Possion's Ratio	0.5	
Yield strength	20	Kpa

The number of turns on the coil was 100, and the distance between the electromagnet and permanent magnet is 1.5 mm. The electromagnetic force (EMF) is a function of the applied current, coil turn and properties of the permanent magnet. The PDMS diaphragm has the following properties: elastic modulus 50 Kpa, Poisson's ratio 0.5, and yield strength 20 Kpa. The diaphragm diameter and thickness were 4 mm and 80 μm, respectively. With the proposed optimized design, a smaller force was capable of achieving the required large deflection. The required EMF to get a diaphragm deflection of 10 μm is 22.3 μN. Fig. 6 shows the variation of the diaphragm displacement with the applied force. A comparison to existing results shows that a circular plate type diaphragm undergoes a greater deflection than other types such as a square or rectangular plate.

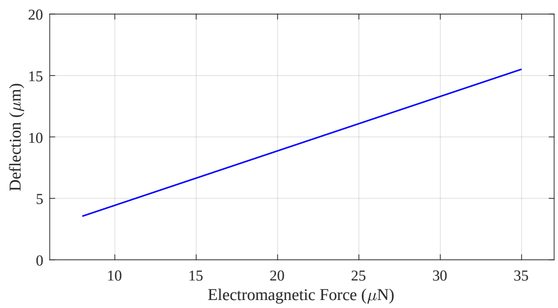

Fig. 6: Variation of Deflection with Applied Force.

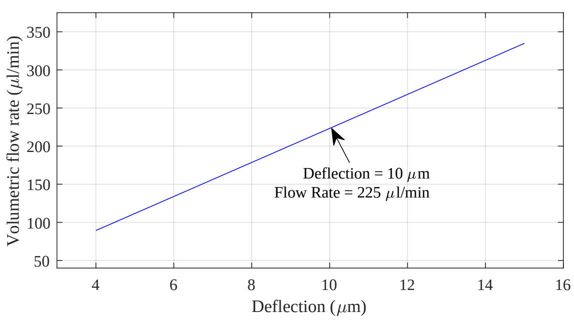

Fig. 7: Volumetric Flow rate as a Function of Membrane Deflection.

The variation of flow rate with input voltage was analyzed from the simulation results. It is seen that flow rate increases linearly with the applied input voltage which supports the fact that membrane deflection also has a linear relationship with input voltage. Fig. 7 shows the variation of volumetric flow rate with membrane deflection, which is a function of input voltage. A pattern independent approach was used for the measurement of power consumption. The power consumption of the proposed system was 12.81 mW, which is 10-30 % less compared to previous work [12], [13].

VI. Conclusions

In this paper we propose a smart drug delivery system in the IoT framework which uses a k-NN classifier for seizure detection and an electromagnetic micropump for drug delivery. Simulink® was used for the implementation and validation of the system. The system level simulation results show that the proposed system enhances the detection accuracy and reduces the power consumption, which makes it suitable for use as an implantable device. The proposed prototype could be useful for epilepsy treatment. In future work we will implement the proposed system for commercial biomedical application.

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