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COMPARISION OF DYNAMIC BEHAVIORS OF STRIATAL POPULATION WITH TWO DIFFERENT NEURON MODELS: HODGKIN-HUXLEY AND IZHIKEVICH

(STRİATAL SİNİR HÜCRELERİN DİNAMİK DAVRANIŞININ İKİ FAKLI NÖRON MODELİ -HODGKIN-HUGLEY VE IZHIKEVICH- İLE KARŞILAŞTIRMASI)

Yüksel ÇAKIR[1]

ABSTRACT

In computational neuroscience, using the tools of dynamical systems theory and modeling the behaviors of neural system is an important issue in order to investigate the mechanisms underlying for neurological disorders and diseases such as Parkinson's and Huntington Disease. In this work, the dynamic behavior of striatal population is investigated using two different scale neuron models: Izhikevich neuron model and Hodgkin-Huxley type model. In the modeling, the influences of network organization are investigated as well. Two different network architectures are used. For all these investigations in-house built MATLAB codes are used. It is shown that Izhikevich neuron model can be used to model the dynamic behavior of striatal neuron populations, with a much simplier representation than conductance-based HH neurons.

Keywords: striatal, Hodgkin-Huxley type model, Izhikevich neuron model

ÖZ

Hesaplamalı sinirbilimde, Parkinson ve Huntington hastalığı gibi nörolojik bozukluklar ve hastalıkların altında yatan mekanizmaları araştırmak amacıyla, dinamik sistem teorilerinin kullanımı ve nöral sistem davranışlarının modellenmesi son derecede önemlidir. Bu nedenle, bu çalışmada, striatal nöral yapıların dinamik davranışlarını modellemek üzere iki farklı ölçekteki nöron modelleri kullanılmıştır. Bular Izhikevich nöron modeli ve Hodgkin-Huxley modelidir. Modellemede, ağ yapılarının etkisi iki farklı yapı için incelenmiştir. Simulasyonlar MATLAB de yazılan kodlar sayesinde gerçekleştirilmiştir. Daha basit bir yapıya sahip olan Izhikevich nöron modelinin striatal nöronlarının dinamik davranışını modellemek için daha uygun olduğu ortaya konulmuştur.

Anahtar Kelimeler: *striatum, Hodgkin-Huxley modeli, Izhikevich nöron modeli*

[1] Istanbul Technical University, Department of Electronics and Communications, Istanbul, Turkey, cakiryu@itu.edu.tr (corresponding author)

1. INTRODUCTION

The striatum is the essential component of the basal ganglia which is associated with a variety of functions including control of voluntary motor movements, procedural learning, routine behaviors or habits . Striatum which receives input from the cerebral cortex is also the primary input to the basal ganglia system. 90–95% of the total neuronal population of the striatum comprise medium spiny neurons (MSN) which have dopamine receptors [1, 2]. The lack of dopamine in the striatum is regarded as a major cause of motor-related Parkinson's disease symptoms, such as tremors, bradykinesia, and postural instability. Therefore, modeling of dynamic behavior of striatum is an important component of work on Parkinson's disease.

Even though the number of work focuses on computational modeling of neural structures such as basal ganglia, cortex, thalamus and striatum are high, the modeling of dynamic behaviors is still a debate subject in the literature due to the complexity of these structures [1-14]. In computational neuroscience, modeling the behaviors of neural system is an important issue in order to investigate the mechanisms underlying for neurological disorders and diseases such as Parkinson's and Huntington Disease. On the other hand, different type of neuron models have been used in the literature for modeling neural structures such as Hodgkin-Huxley (HH) model, integrate and fire model, leaky integrate and fire and Izhikevich.

One of the mostly used models is Hodgkin-Huxley (HH) or conductance based model [3]. It is biologically realistic for the nerve cells, and the most widely used mathematical model of neuron behavior. This model is capable of defining the effect of especially potassium and the sodium channels. By adding new ion channels to the structure, it is possible to exhibit the various behaviors such as bursting and tonic bursting. In the work by Batista et al. [4], HH model is used for modeling the small-world network of neurons with chemical synapses. McCarthy et al. [5] use HH conductance based model for simulating the behavior of MSNs.

A simple model that reproduces the behaviors such as spiking, bursting, and mixed mode firing patterns is presented in the work by Izhikevich [6]. In this work, it is stated that HH model is computationaly prohibitive compared to Izhikevich model without presenting the model responses. Izhikevich [7] compared the neuro-computational properties of spiking and bursting models such as HH, integrate and fire, quadratic integrate and fire, Izhikevich, Morris-Lecar. However, the dynamic behaviors of the network is not depicted. HH model used for comparision is the original one which consists of only sodium and potasium currents.

In the work by Liu et al. [8], hybrid Izhikevich neuron model is used to capture the dynamical characteristics of the basal ganglia–thalamic neuronal network that can exhibit physiological and pathological characteristics of Parkinson's Disease. The influences of the model parameters are investigated through a detailed analysis.

In this work, the purpose is to compare the dynamic behaviors of striatal neurons using HH and Izhikevich neuron models with two different network structures. In the work by Izhikevich [6], even though it is stated that computational time is high in HH model, the level of this difference in the computational time is not given and the dynamic behavior of neuron populations are not depicted also. On the other hand, Izhikevich [7] compared the different models. However, the dynamic behaviors of neurons in a network are not depicted. Apart from the work by Izhikevich [6, 7], in this work, the dynamic behavior of MSNs with two different network structures are investigated using HH and Izhikevich models. Another difference of this work from the already existing works in the literature, is that not only sodium, potassium and leak currents in the equation defining the potential difference of cell membrane of HH model is used, but also the high threshold calcium current, after hyperpolarization calcium current and voltage gate potassium current are considered influenced from the works of Terman et al. [9] and Shen et al. [10] to represent the behavior of MSNs. The equations related to striatal population is given and the simulation results obtained using the in-house built MATLAB codes are discussed. The simulation results show that using simple neuron model gives almost the same results as the complicated neuron model and the networks of neurons do affect the collective behavior. Comparision of the computational times for both models reveal that Izhikevich model is much proper one for large scale networks.

2. HODGKIN-HUXLEY NEURON MODEL

The dynamical behaivor of the stratium cell potential is modelled by the differential equation given in Eq. 1.

$$C_m \dot{v}_{Str} = I - I_L - I_K - I_{Na} - I_{L_{Ca}} - I_{AHP} - I_{Ca} - I_{Kv1} \quad (1)$$

Where, C_m is the membrane capacitance per unit area and v_{str} denotes the membrane potential of the striatum. I_L is the leak current, I_K, I_{Na} are ionic currents related to the ion channels embedded in the neuron membrane. I_{LCa}, I_{AHP} and I_{Ca} are high threshold calcium current, after hyperpolarization calcium current and calcium current, respectively. Ohmic leak current, I_L, which is carried mostly by Cl^- ions, is defined as in Eq. 2.

$$I_L = g_L (v_{Str} - V_L) \quad (2)$$

Where, g_L is the leak conductance which is constant in the model. V_{str} and V_L are stratium membrane voltage and equilibrium voltage, respectively. K^+ current with four activation gates which is one of the four major currents is defined as Eq. 3.

$$I_K = g_K n^4 (v_{Str} - V_K) \quad (3)$$

where n is the activation variable for K^+, the parameter g_K (mS/cm^2) is the K^+ conductance and ($Vstr$ -V_K) is the K^+ driving force. n^4 is the probability that a potassium channel is open. The voltage-gated transient Na^+ current is defined as Eq. 4.

$$I_{Na} = g_{Na} m^3 h (v_{Str} - V_{Na}) \quad (4)$$

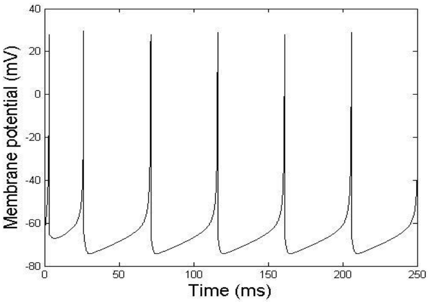
Where m (h) is the probability of an activation (inactivation) gate being the open state. The definitions and details of L-type calcium current, afterhyperpolarization K^+ current (I_{AHP}), Ca current and voltage gated potasium current (I_{KV1}) can be found in [9, 10].

3. IZHIKEVICH BASED NEURON MODEL

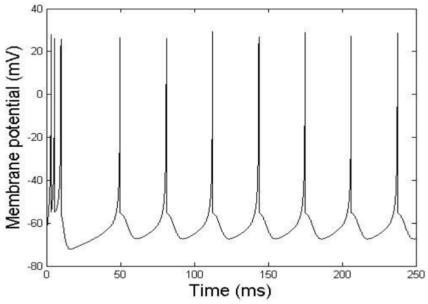
Izhikevich neuron model, which is a phenomenological model differs from conductance-based HH-type models. Apart from HH model, instead of introducing all of the ionic currents, the model was designed to reproduce firing responses. The equations of Izhikevich neuron model are given in Eq.5.

$$\begin{aligned} \dot{v} &= 0.04v^2 + 5v + 140 - u + I \\ \dot{u} &= a(bv - u) \\ v &\geq 30 \;\; v \rightarrow c, u \rightarrow u + d \end{aligned} \qquad (5)$$

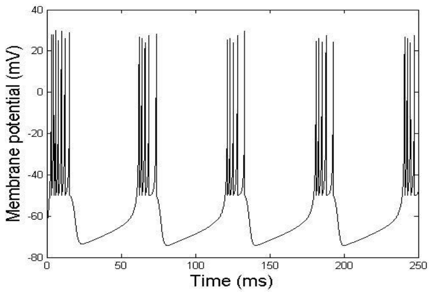
where v and u are dimensionless variables, represents membrane potential of the neuron and membran recovery respectively. *a, b, c,* and *d* are dimensionless parameters. When membrane potential threshold reaches 30 mV, v and u are assigned to the values given in the last expression of Eq. 5. *I* is current input including synaptic current and external applied current. The simulation results of Izhikevich model for different set of parameters are depicted in Figure 1. These results are obtained from in-house built MATLAB codes.



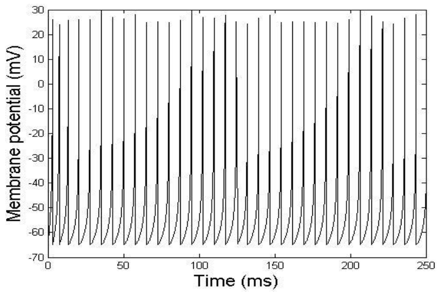
a) Regular spiking (RS)



b) Intrinsically bursting (IB)



c) Chattering (CH)



d) Fast spiking (FS)

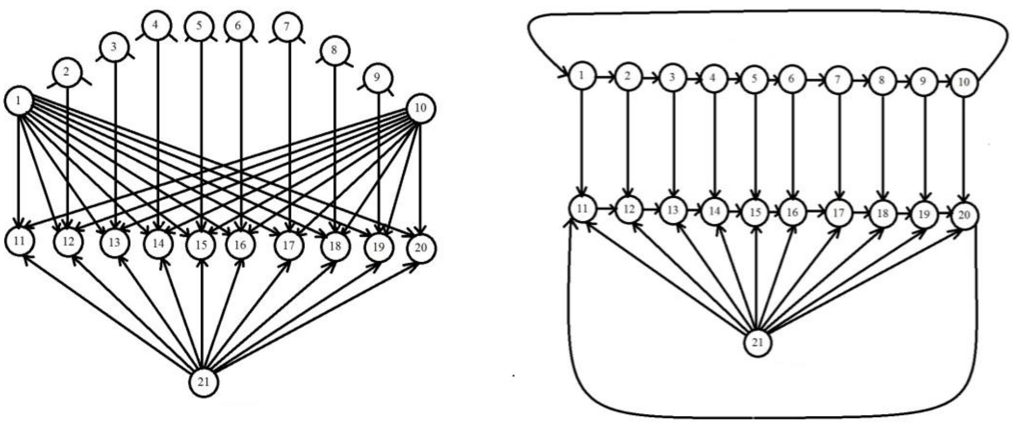
Figure 1. The simulation results of Izhikevich model for different set of parameters.

The different set of model parameters reveal different neuron behaviors such as regular spiking, fast spiking and chattering.

4. NETWORK STRUCTURE

The dynamic behavior of a population of neurons in striatum is modeled for two different architectures using two neuron models to investigate the role of network organization and the role of neuron models. The principal neurons of striatum are MSN which are GABAergic cells. It means that they inhibit their targets with small cell bodies and dendrites. Therefore, they are classified as inhibitory neurons. Depending on the species, MSNs comprise 90–95% of the total neuronal population in the striatum of the basal ganglia and they suppress the other structures which are affected by the striatum. On the other hand, interneurons comprise only ~10% of the striatal cells [1, 2].Considering these ratios, as in a striatal microcircuit, in all architectures one interneuron is considered along with 20 medium spinny (MS) neurons.

In each topology given in Figure 2a and 2b, there are three layers, the first two layers comprise of ten MS neurons each, while the last layer is composed of a single interneuron. The interneuron in the third layer is connected to every neuron in the second layer and inhibits their activities, in two architectures. In the architecture, given in Figure 2(a), every neuron in the first layer is connected to every neuron in the second layer unidirectionaly, so all-to-all connection is considered and the network is a feedforward. In the second architecture, every neuron in the first and second layer has inhibitory unidirectional connection with its neighboring neuron, so forming a feedback loop giving rise to a network architecture with feedback. There is no known topological information about the organization of neurons at this level, so in this work looking at the different topologies would inspire about the role of the neuronal organization, and this information could be informative about the mechanisms of information processing in the brain [15].



a) b)

Figure 2. The network architectures for striatal neuron populations with
a) all-to-all feedforward, b) one-to-one feedback

5. SIMULATION RESULTS

5.1 Simulation results of HH neuron model

In order to model the network, the connection between neurons should be defined. The current $I_{stri \rightarrow strj}$ which represents the synaptic input from neuron to neuron is included into Eq.1.

as $I_{stri \to strj} = \alpha_j (v_{strj} - E)$. α_j, the synaptic conductance is modelled as a constant depending on a parameter β as $\alpha_j = 1.1 \cdot 10^{-4} \cdot \beta$.

The simulations results of HH neuron model for the first architecture (Figure 2a, all-to-all feedforward) are given in Figure 3.

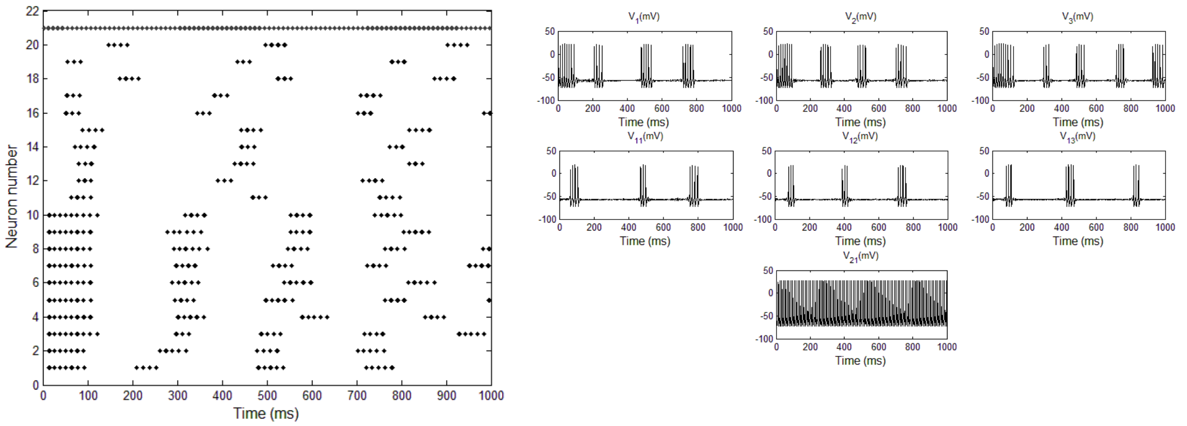
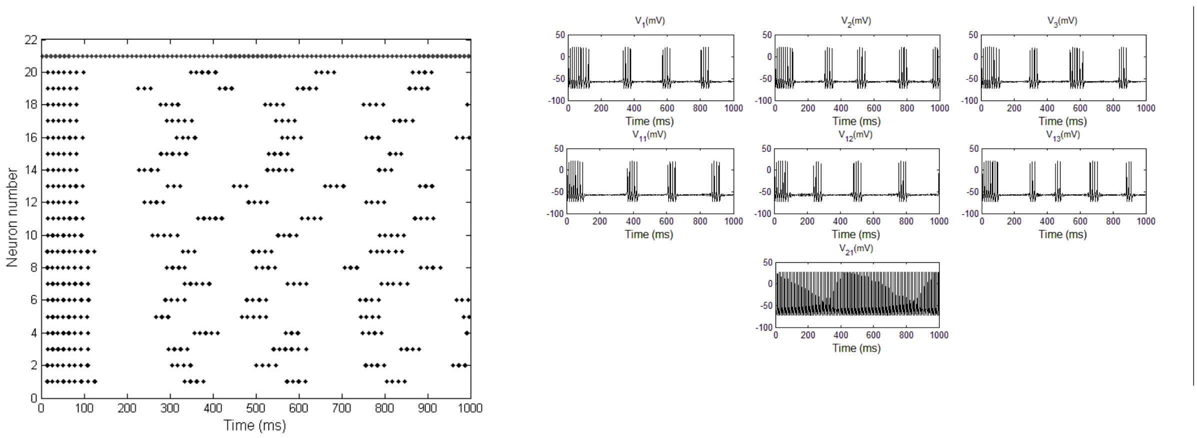


Figure 3. The raster plot of 21 neurons and the dynamic behavior of neurons in the first network.

For the feedforward structure in Figure 2(a), as there are more connections from the first layer to second layer, and since the synaptic connection between MS neurons are inhibitory, the neurons in the second layer fire less, as it can be followed from the raster plot in Figure 3. It is observed that there is a period of firing and silence. For this structure, changing the synaptic conductance, affect the spiking activity. As β increases, the spiking activity in the second layer decreases and for $\beta = 500$, there is almost no spiking neuron in the second layer. Thus, with this architecture, the inhibition between MS neurons affect the overall neuronal activity more.

The rasterplot and membrane potentials for the second architecture given in Figure 2(b) are depicted in Figure 4.



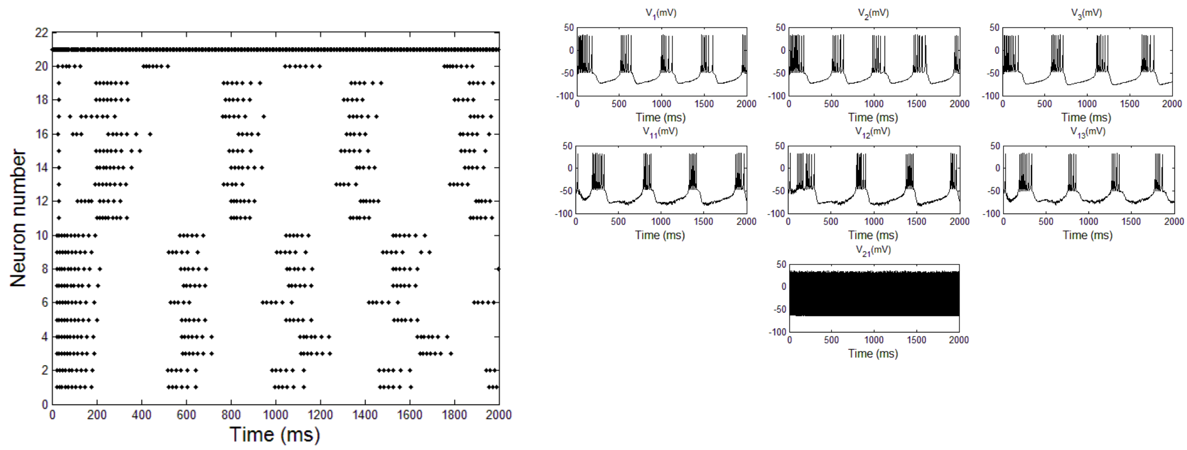
a) Raster plot b) The dynamic behavior of neurons

Figure 4. The simulation of the network in Figure 2(b) with HH neuron model

In this network, the neurons in both layer have unidirectional connection beginning from the neuron with smallest indice to the one with largest indice in the layer. In this architecture, changing the synaptic conductance, has a negligible effect on the synaptic activity, though there is not difference between the activity of first and second layer neurons, for larger β values, the overall activity is lesser.

5.2 Simulation results of Izhikevich neuron model

In the modeling ot the network structures given in Figure 2 with Izhikevich neurons, the chattering behavior is considered for the first two layers and the inhibitory neuron is modeled as fast spiking neuron. So, the neurons in the first two layer will be behaving as in Figure 1c, while the inhibitory neuron behave as in Figure 1d. The connections are constant. Depending on being excitatory or inhibitory connections, input current is either has a positive or negative random value. Input current is modeled as $I_{input} = I_o + \alpha\mu(t)$, where I_o is mean current, α is a constant and $\mu(t)$ is Gaussion noise with zero mean. I_{input} takes value between 10 and 20 for MSNs, 150 and 300 for interneuron.



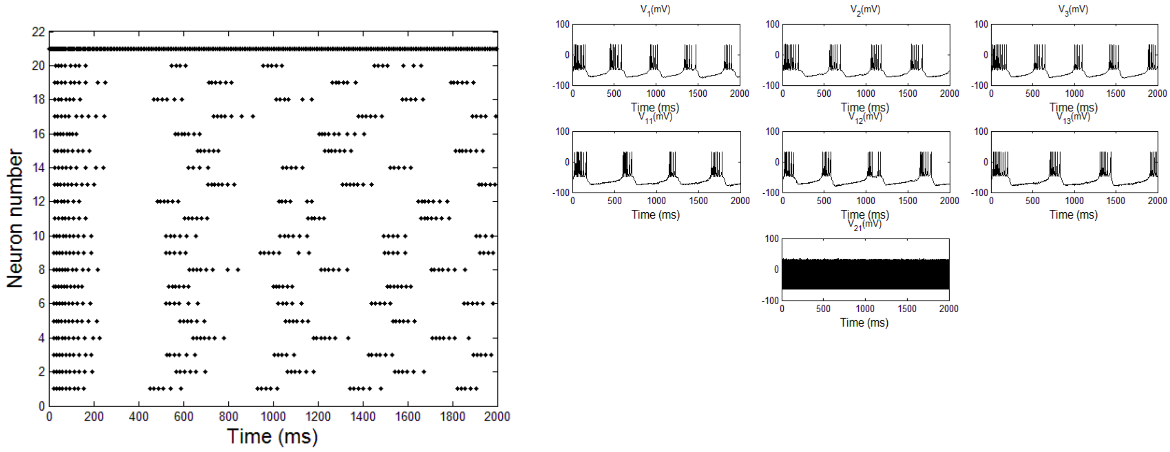
a) Raster plot

b) The dynamic behavior of neurons

Figure 5. The simulation of the network in Figure 2a with Izhikevich neuron model.

The raster plot given in Figure 5 is the same network architecture as the raster plot obtained with HH neuros in Figure 3. When it is compared to the raster plot given in Figure 3 where, HH neurons are used, the activity in the second layer seems to be more, but in Figure 5, the synchronization of neuronal behavior is more, and the inhibiton of the first layer on the second layer can be observed more clearly. While the neurons in the first layer fire, the neurons in the second layer become quite and when the neurons in the first layer become quite, as the inhibition of these on the second layer is removed, the neurons in the second layer fire.

The raster plots and dynamic behaviors given in Figure 6 are the results of architecture (2b) and their, HH model correspondence are the raster plots and dynamic behaviors given in Figure 4.



a) The raster plot of 21 neurons

b) The dynamic behaviors of neurons

Figure 6. The simulation of the network in Figure 2b with Izhikevich neuron model.

The computational time spent is compared for both neuron models and depicted in Table 1.

Table 1 Execution time for two models and networks

	1. network	2. network
Hodgkin-Huxley model	5434.1 s.	6425.4 s.
Izhikevich model	18.4749 s.	19.7543 s.

Table 1 reveals that as expected, even for small networks, computational time is high for HH model since it contains current equations for ion channels. Especially for large scale neotworks, Izhikevich model is preferable.

6 CONCLUSIONS

In this work, to investigate the influence of striatal neuron network, two network architectures are used with two different scale neuron models. The neuron models are HH model and Izhikevich neuron model. In addition to investigating the influence of network architecture, the simulation results of two different scale models are compared. It is seen that using simple neuron model gives almost the same results as the complicated neuron model and the organization of neurons do affect the collective behavior. Since computationl time in HH model is high compared to the time in Izhikevich model, it is convenient to use Izhikevich model for large scale networks of real life applications.

The results given with the raster plots can be even more informative if this work is repeated considering more neurons and frequency analysis is carried. In order to investigate frequency analysis, it is clear from the results obtained here, that using Izhikevich neuron model instead of detailed HH neuron model does not make qualitative difference, while computational time is reduced significantly.

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CV/ ÖZGEÇMİŞ

Yuksel Cakir, Dr.

He received B.Sc. degree from Istanbul Technical University; Faculty of Electrical and Electronics Engineering, Electronics and Communication Engineering Department and he received M.Sc. degree from Institute of Science and Technology, Computer and Control Engineering Department, and Ph.D. degree from the same institute Electronics and Communication Engineering Department. He joined Istanbul Technical University, Electronics and Communication Department as research assistant in 1987, where he is now lecturer. He worked in the summer of 2008 at UTL, Bangalore, India on embedded systems. His research interests include optimization, artificial neural networks and non-linear dynamical systems.

Yüksel Çakır, İstanbul Teknik Üniversitesi Elektrik Elektronik Fakültesi, Elektronik ve Haberleşme Mühendisliği Bölümünden mezun olup İstanbul Teknik Üniversitesi Fen Bilimleri Enstitüsü, Kontrol ve Bilgisayar Mühendisliği Bölümünden yüksek lisans derecesi, aynı enstitünün Elektronik ve Haberleşme Mühendisliği Bölümü'nden doktora derecesi almıştır. Yüksel Çakır 1987 yılında Araştırma Görevlisi olarak İstanbul Teknik Üniversitesi, Elektronik ve Haberleşme Bölümünde çalışmaya başladı halen Öğretim Görevlisi olarak çalışmaktadır. Gömülü sistemler konusunda 2008 yılının Hindistan'ın Bangalore şehrinde yer alan UTL kuruluşunda çalıştı. Araştırma alanları optimizasyonu, yapay sinir ağları ve doğrusal olmayan dinamik sistemlerini kapsar.