博士論文（要約）

Qualitative-modeling-based digital silicon neuronal network models

(定性的モデリングアプローチに基づいたデジタルシリコン神経ネットワークモデル)

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Silicon neuronal networks, an electronic-circuit equivalent of the nervous system achieved by highly advanced silicon technology, have been gathering increasing attention as a promising new paradigm for computing systems. The nervous-system informed parallel, distributed structures of such electronic circuits allow for the high-speed simulation of large-scale neuronal networks with low-power consumption. The circuits consist of silicon neurons, silicon synapses, and a transmission bus of the spike signal. The silicon neurons comprise a dedicated circuit that solves the differential equations of the spiking neuron model. Although diversified spiking neuron models have been studied, only the integrate-and-fire-based models are commonly used in large-scale silicon neuronal networks due to their extremely low computational cost. However, the model abbreviates the spiking process and cannot reproduce a wide variety of neuronal firing properties.

The present thesis developed a qualitative-modeling approach for the digital silicon neurons that allows for the reproduction of a wide variety of firing properties with far fewer circuit resources. The resulting neuron models can cover a variety of neuron classes including regular spiking, fast spiking, intrinsically bursting, low-threshold spiking, elliptic bursting, and parabolic bursting, with approximately one-hundredth fewer resources than the ionic-conductance models. The similarity of both models was quantitatively confirmed by measuring the statistical properties of the spike sequences in each neuron class. The parameter sets of the models are semi-automatically determined based on a metaheuristic approach. This automatical parameter tuning method is essential to faithfully replicate the large-scale nervous system at the single-neuron level because the manual parameter fitting requires an unrealistically extensive amount of human resources. This study aimed to provide a fundamental tool that satisfies the demand for large-scale neuronal-network simulation with closer-to-biology models.

Further, we constructed a biologically-plausible small neuronal network by applying the qualitative-modeling approach. The strength of the excitatory synapses is autonomously updated based on the spike-timing-dependent plasticity, which allows the network to detect the spatiotemporal spike patterns from a random spike sequence. We have elucidated that some firing properties improve the performance of the spike detection and that the slow neuronal dynamics enable the network to stably find the spike patterns in response to the input data whose firing frequency dynamically changes. These results emphasize the importance of neuronal firing properties for the purpose of engineering, although these ii firing properties have been ignored in most other silicon

neuronal networks. Furthermore, this investigation may provide a new direction that can improve neuromorphic information processing.

We also propose qualitative multi-neuronal models based on the sensory organ of the fruit fly, Drosophila melanogaster. Though the sensory organ is known to detect sound, gravity, and wind, the underlying mechanisms by which such perception is achieved remain unclear. Our qualitative-modeling method allows for the proposal of brief draft models that can explain input-output characteristics observed in biological experiments. These models intend to provide a foundation for the elucidation of the mechanism of the sensory nervous system in the insect as well as the construction of a neuromorphic sensing system.

The results presented in this thesis will contribute to the implementation and utilization of a wide variety of neuronal firing properties, thereby providing a new paradigm in neuromorphic engineering.