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学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Physical Computing Systems: Theory, Implementation and Functionality
（物理計算システム: 機能実現への理論と実践）

Unconventional computing (UC) is a novel formalism as a post-Moore solution that stems from a perspective of smaller, faster, and more energy-efficient methodology. Exploring unbounded physical phenomena serving as computing resources is the main goal of UC research, but it is difficult to take these findings as guidelines due to the diversity of physical phenomena and the lack of a unified paradigm. Before UC formalism can grow and refine into a unified formal theory, it is necessary to explore the computational paradigms available for existing physical devices, but the most important aim should be providing guidance for future system design. One UC paradigm that utilizes dynamic systems, reservoir computing, is widely discussed due to its arbitrary and diverse physical implementations. An important objective of this paper is to comprehensively analyze different schemes of RC structure design and nonlinear function selection, and to observe their respective effects on information processing. The ultimate purpose is to validate the usability of proposing schemes and design rule, then develop a small, simple, fast and low power-consumption physical device based on them. Additionally, attempts to find a suitable UC paradigm for existing devices according to their own characteristics is also necessary for future system design.

In Chapter 2, we defined a simple structure of reservoir from its mathematical definition matrix and give it the simplest form of realization, that is, one pair of diodes. Instead of treating RC as a "black box" like most schemes of physical RC design, we realized a simple controllable physical system by external parameters so as to provide I-V curve of diodes with dynamics and to observe their effects. This scheme originates from the design idea of independent processing nodes, and on this basis, the influence of nonlinear function of processing node and node arrangement structure are explored respectively. Nodes structure has greater effects on NARMA2 task, short-term memory capacity task and classification task than its nonlinear function. A large number of random and strong connections between nodes ensure the echo state duration of original information in the network, which is conducive to short-term memory capacity and tasks requiring high memory capacity but interferes with the classification of processed information. Reservoir with sparser and weaker connections on the other hand solves both NARMA2 task and classification task well. Our parallel-group structure works the same with such network in the performance of both NARMA2 and classification task, indicating that a sparse interconnectivity of all nodes that are commonly accepted in reservoir can be replaced by regular connections of segmental nodes. Besides, even parallel-node structure showed acceptable accuracy on classification task, although it could not solve the NARMA task well. This opens up a new path for the design and selection of physical RC systems in the future because the parameters of the parallel structure are directly reflected in the definition matrix of reservoir and thus can be better

correlated with inherent parameters of the physical system, facilitating the adjustment and control of the system.

In Chapter 3, a new physical device, sets of planar parallel electrodes, is designed based on the parallel structure to further verify its practicability. The size and distribution of the electrodes cannot be changed, which means that the structure of the reservoir is fixed. Solution that dripped to the surface of the electrodes provides different nonlinear functions owing to their specific I-V characteristic, and the slightly different electrochemical reactions occurred on different electrodes act as the feedback gain of processing nodes. It is shown in short-term memory capacity results that no matter what solution is added on the surface, there is a certain degree of interaction between the adjacent electrodes, which implies the feedforward gain in the parallel-group structure described in Chapter 2. Therefore this device exhibited a prediction error matching that of parallel-group structure in the same NARMA2 task. Compared to distilled water, solution with complex REDOX reactions display more dynamical I-V characteristics, which aid in reproduction of periodic signals but pose a challenge in solving higher-order nonlinear problems. In the approximation of those higher-order nonlinear problems, protons contribute greatly to the computational power of this system. This is concluded because system lost computing power when the solvent was replaced by nonprotonic solvent.

Next we demonstrated how to apply appropriate UC paradigm to existing physical systems based on their own characteristics in Chapter 4 and Chapter 5. Chapter 4 explored the feasibility of performing stochastic computing paradigm on a SWNT/POM network with stochastic transfer process of charges inside. At the level of real device, the magnitude of output current was controlled by the voltage on the grid under the condition of a stable source-drain voltage. The output current showed sinusoidal under the control voltage of sinusoidal excitation. In addition, the spike density of the output current increased with the number of times applying the gate voltage of the same magnitude. Above observations are realized in experiment and the results are repeatable. On the simulation level, we achieved the gradual growth or decay of the current spike density along epoch with big VG or small VG Each epoch includes 3 clock cycles for input stimulus and 256 clock cycles for weights updating. Such results show a great potential of SWNT/POM network device to replace encoders, decoders and memory in fully-implemented hardware circuits for stochastic computing. Chapter 5 explored how to use the improved readout circuit on a dopant network (i.e., boron dopants in silicon) generating memory effect to process temporal and spatial signals. It is found that the dopant network has a similar effect on spatio-temporal signal processing as the maximum pooling operation, thus the data processed by dopant network can be used directly on linear classifier. The number of neurons required for classification is much smaller than the size of convolutional neural networks, representing the great advantage of dopant network as a convolution kernel.

Overall, the performed research has provided new insights into the design and utilization of physical computing systems. Starting from simple design principle and small device, the theory of UC is explored and supplemented, and a different way is pointed out for the future system design and development. The design and assessment of different physical UC schemes can be improved based on the outcome of this research.