学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Bio-Inspired Electronic Circuits and Stochastic Information Processing Systems exploiting Noise and Fluctuations

（ゆらぎを利用する生物的な電子回路と確率的情報処理システムに関する研究）

Current technological demands look for smaller, faster and more power-efficient systems. However, such demands are limited mainly by physical properties of devices (e.g. size of transistors, increase of electrical noise, etc.). At this point alternative solutions may have a response for such demands. The study of biological systems may offer a different perspective to fulfill such requirements. Biological structures have been optimized during millions of years of evolution resulting in power-efficient, fast and compact systems that are resilient against noisy and hostile environments. Although, no electrical system has been able to emulate any biological structure in their totality, neuromorphic systems have already proved to be efficient in many engineering applications.

This thesis is inspired specifically by how some biological structures use noise to improve determined tasks. The utilization of noise to enhance performance is a well-studied phenomenon and it is known as stochastic resonance (abbreviated as SR). Examples of SR in nature are found inside mechanoreceptors of some insects and fishes to detect weak signals from the environment, it is also observed in the human sensory system, as well as at molecular level to detect low-amplitude stimuli inside nervous system. And at system level, it is also involved in the evolution of human creativity, imagination and decision-making processes. At large-scale natural phenomena, SR has an effect in the ice age transitions.

The use of noise to improve certain tasks could seem counterintuitive from the electrical engineering point of view; however nature has given us many examples of the positive utilization of noise. Noise and fluctuations are inherently part of nature; and biological systems have already self-adapted to include external and internal fluctuations in their processing as a positive factor; in this sense, SR has been already exploited by biomedical engineers, just to mention some remarkable examples on the improvement of silicon cochlea, balance control systems and life-support ventilators, where the introduction of noise is a key factor for a more precise emulation of these artificial systems. Moreover, it has been also utilized in engineering systems such as electrical sensors to detect weak stimuli, signal amplification and noise-induced synchronization circuits.

This thesis presents two main applications related with SR and its applications. The first case is based on the study on how electrical spikes are transmitted along long axons inside the nervous systems. In this process, due to the variability of conductance among stages, the amplitude of electrical spikes may not be enough to excite next stage. However, it has been discovered that internal fluctuations inside node axons may enhance signal transmission. This idea could be mimicked by electrical systems to transmit signals efficiently in the presence of mismatches. Simulation results show that with the introduction of an optimal amount of noise, signal transmission is improved in the presence of

mismatches.
The second part presents a novel application of the SR effect in the field of digital systems. Considering the problems that current devices are facing due to an increment of parameter variability (it may provoke malfunction of electrical chips) and demands for lowering their power consumption, it is utilized noise to design logic gates with three main characteristics: low-power consumption, parameter-variability tolerance and a stable output regardless the introduction of noise. This gates were called SR gates. Simulations and experimental results show their effective performance on the recovery of logic functions in the presence of parameter variations of transistor (such as threshold voltage). However, due to their dependence on stochastic processes, their response presents an unpredictable delay. Therefore the most suitable application is found in the field of asynchronous circuits to design delay-insensitive circuits. Therefore the third part of this study is concentrated in the application of the SR gates to design asynchronous circuits. Synchronous circuit designs have been offering a robust solution for many years, however, considering the current challenges of VLSI circuits, asynchronous circuits may offer a better solution for designing faster, smaller and less power consuming circuits.
Finally, biological systems work inherently in noisy environments and during years of evolution they have self-adapt to these conditions, either by avoiding it or including it as a beneficial part. Towards the next generation of processors, to design more noise- resilient and efficient circuits, a positive collaboration of noise and fluctuations could be a necessary stage to achieve it.