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Three dimensional memristor-based neuromorphic computing system and its application to cloud robotics☆

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ABSTRACT

Neuromorphic computing based on three-dimensional inetgraed circuits (3D-NCs) offers a novel hardware implementation of neuromorphic computing, and provides high device density, massively parallel signal processing capability, low power consumption, and direct analog signal processing capability. In this paper, by replacing conventional CPUs based on Von Neumann architecture with 3D-NCs, a novel neuromorphic computing based cloud robotics (NC-robotics) system is proposed, which is constructed by 1) cloud server center using 3D-NCs as computing units, 2) neuromorphic robotics based on neural network control technology. Besides the benefits of normal Cloud Robotics platform, this NC- Robotics system has more advantages on massive parallel-computing, analog signals processing, and lower power consumption. In order to implement this NC––Robotics system, a novel 3D-NCs architecture combining vertical RRAM structure is investigated and its concise equivalent circuit model is created, evaluated, and analyzed through SPICE simulations.

1. Introduction

The concept of cloud robotics has been conducted for many years in various applications, such as unmanned aerial vehicles (UAVs), warehouse robotics, home automation systems, self-driving vehicle [1], etc. Unlike traditional off-network robotics with isolated data processing that cannot communicate with each other, the robotics in cloud possess the capability of sensing real world data/signals and updating them to cloud side server for further processing and computing. The topology of cloud robotics system is illustrated in Fig. 1. With the assistance of powerful computational resources on the server side, robotics in the cloud can share knowledge/information, learn from each other, access global library of images, maps and object data centers, and accomplish tasks collaboratively.

For now, the computing units in both server and robotic sides are designed in conversational CPUs, which is based on Von Neumann architecture. This type of architecture separates central process unit (CPU) and memory, as exemplified in Fig. 2. The data communication between the CPU and memory is through the parallel data bus whereby the speed of the data bus dictates the system achievable data rate. As the data rate keeps elevating, the parallel bus ultimately becomes the energetic and speed bottleneck. The robotics created by using this type of CPU as computing unit has been improving the productivity and quality of our society for many years. However, the abilities of these robotics pales comparing with the animals and

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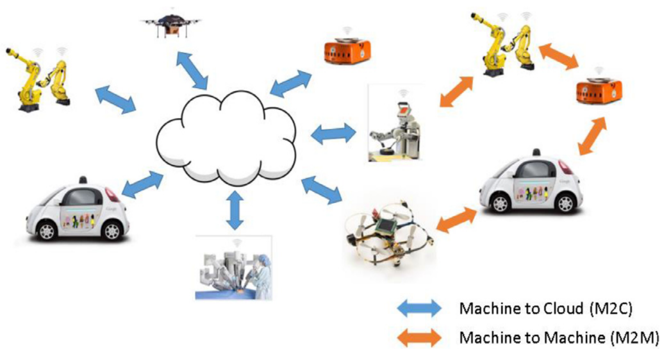

Fig. 1. Cloud robotics concept diagram.

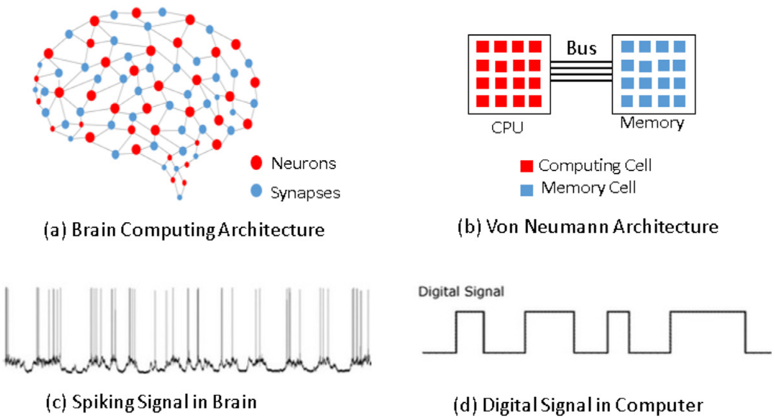

Fig. 2. Comparison between brains computing system with conventional Von Neumann computing system. The bus in traditional Von Neumann is energetic and speed bottleneck.

insects, which processes signals using neurons as the biological computing units. These biological organisms survive in dynamic environments for centuries and display extraordinary flexibility and adaptability that all artificial intelligent system lack for now. Moreover, the computing system based on the neural network also can efficiently control the body to make rapid and coordinated response corresponding to the changes from the physical world. For example, birds can constantly adjust the flying height and direction to avoid obstacles through visionary signals captured by their eyes. These visionary analogic signals are processed and analyzed in their several grams brain with extremely low power consumption.

These impressive capabilities of computing and controlling capabilities come from the unique nervous system structure macroscopically and the signal encoding methodology microscopically. The nervous system does not only exist within the brain, but also extends throughout the whole body as illustrated in Fig. 3. This neural network based response/control system inspired the dedicated researchers to develop robotics with the neural network control system [2] and to propose the neuromorphic computing concept [3], as demonstrated in Fig. 4.

Although many neuromorphic ICs have been applied to robotics field, there is still a lack of cloud server assembled by neuromorphic ICs connecting another neuromorphic robotics. In this paper, a new purely neuromorphic computing based cloud robotics system is proposed, as illustrated in Fig. 5. This novel Neuromorphic Cloud Robotics (NC-Robotics) system replaces conventional computing units (CPU + Memory) with neuromorphic ICs on both robotics and server sides. Each neuromorphic robot in the cloud network can seamlessly connect to the neuromorphic server for further analog signal processing.

In order to build neuromorphic cloud server, more powerful and efficient neuromorphic IC architecture and technology need to be investigated. Table 1 summarizes the existing state-of-art fabricated "analog" and "digital" neuromorphic computing chips. To the best of our knowledge, all reported fabricated neuromorphic chips employ traditional two-dimensional integrated circuit (2D-ICs) design methodology and complementary metal–oxide–semiconductor (CMOS) technology.

Although the 2D-ICs listed in Table 1 offer more neuromorphic computational capabilities than the conventional ICs using Von Neumann architecture, their inevitably inherent limitations hinder them to have a compelling performance close to the human brain. To be more specific, with the number of neurons increasing, 2D neuron placement becomes incapable due to its routing density increasing linearly with the number of the connections. In order to satisfy the desired connections, longer routing and larger die area are the inevitable consequences, hence larger power and cost consumptions as a result. Furthermore, to a certain extent, 2D connections become prohibitive longer, which counterpoises the benefit offered by neuromorphic computing. For example, in Table 1, each neuron of TrueNorth chip only connects 244 synapses. The same