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Design automation of cellular neural networks for data fusion applications

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ABSTRACT

In this study, a novel methodology for the design automation of cellular neural networks (CNNs) for different applications is proposed. In particular, an evolvable algorithm has been developed providing the ability to generate the netlist of the requested CNN in any desired dimension through a very simple procedure, which greatly simplifies the network design process, without the requirement of any relative design knowledge. Furthermore, the user is also granted with control over the selection of the overall function of the network, in order to make it suitable for a variety of data fusion applications. Moreover, the generated netlist can be imported in the SPICE Cad System, resulting in the automated generation of the network schematic, which can be used for the circuit hardware implementation. More specifically, a tutorial 10×10 CNN model is generated via the proposed methodology for use in a data fusion and control application. The produced model is tested by its application to a real distributed temperature sensor network for an application involving the attainment and the conservation of the thermal stability of a system. The data transmission is implied through the use of a set of wireless transmitters–receivers. Finally, a series of experimental results on real world conditions are presented, proving the effectiveness and the robustness of the generated CNN and respectively of the proposed methodology.

1. Introduction

Nowadays, spatially distributed sensor network systems are widely used in both domestic [1] and industrial domains [2]. In most cases, these networks consist of autonomous sensor units, which are cooperatively used in order to measure and monitor physical or environmental properties, such as temperature, pressure, motion, position, light intensity, etc. These properties act as the stimulus to the sensor, the output of which is often conditioned and processed to provide the corresponding measurement of the physical property. Sensors are generally part of a larger system consisting of signal conditioners and various analog, or digital signal processing circuits. That system could be a measurement system [3,4], a data acquisition system [5–8], or a process control system [2,9,10], for example.

Ubiquitous computing envisages everyday objects as being augmented with computation and communication capabilities. While such artifacts retain their original use and appearance, their augmentation can seamlessly enhance and extend their usage, opening up novel interaction patterns and applications. Networks of wireless sensors are the result of rapid convergence of three key technologies: digital circuitry, wireless communications, and Micro-ElectroMechanical Systems (MEMS). Advances in hardware technology and engineering design have led to reductions in size, power consumption, and cost. This has enabled compact, autonomous nodes, each containing one or more sensors, computation and communication capabilities, and a power supply [11].

Specifically, in the case of data control and automation systems, distributed smart sensors comprise the most significant tool towards meeting the corresponding prospective goals in each application. *Smart sensors* provide the feature of implying the sensing, the conditioning and the processing part of the system within the cell of a single device [12]. Some practical examples of such smart devices can be observed in a variety of everyday applications including smart houses [1,13,14], hotel automation systems [15], robotics [16], industrial process control systems [2,17,18], automation in aviation [4,19], environmental control systems [6,8,20,21], etc. The problems that these systems are usually meant to both confront and solve are often related to some global system aspect. This is the exact reason why these sets of sensors should not merely operate autonomously, but they ought to be part of a wide network, where each entity should interact with the rest, resulting in some sort of global controlling function [22,23].

In order for that global function to be achieved, one of the available parallel computing logical models should be adopted. In that way, the entire spatially distributed sensor system would become a parallel sensing network, which would provide us with the expected global properties and behavior. Some of the most effective and common computational models so far are *neural networks*, *cellular automata* [24], *genetic algorithms* [25] and *fuzzy logic*

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systems [26]. Each one of these models implies a variety of properties and features, that can be desirable or not depending on the specific requirements of the current application. For that reason, an extensive study of these requirements is often of utter significance, so as to be able to make the right selection. Alternatively, a combination of the properties of the foretold models could result in a hybrid computing system, which could include only the desired features.

In this study, the main interest is the fusion and the control of data acquired by a network of multiple distributed sensors via the utilization of an analog *cellular neural network* (*CNN*) [27–29]. CNN is a hybrid logical model, which implies a lot of great features that makes it appropriate for use in control applications. CNN consists of identical structural computational entities, the cells, which are connected locally to each other. However, despite the total lack of global connections, this network of cells presents a global logic function and is capable of dealing with very complex computations. In specific, except for the fast parallel computing ability, CNN implies additional features such as: continuous time global dynamic behavior, great flexibility regarding to the shaping of its behavior pattern, simple and smart structure, great stability, low cost implementation and great robustness. However, one of its most significant features refers to its high accuracy, which comes as a result of its analog circuit nature. In [30], a CNN architecture has been proposed for realizing multi-sensor data fusion and distributed control systems, whereas in [31] CNN is proposed as a decentralized control paradigm for robotic locomotion. In addition, in [32] a CNN approach is discussed as far as distributed sensor networks are concerned. The specific computational tool implies the local connectivity and the global data processing features, however, it is only limited on one-dimensional circular topology. In the end, another remarkable feature of the CNN is the flexibility that it provides in the setting of its total functionality. Some examples of template programming of CNN can be found in [33–35].

In the length of this manuscript, a novel methodology is proposed for the design automation of CNN circuits in any desired dimension, in association to the current application needs. In other words, an algorithm has been developed, which takes advantage of the already known circuit structure and topology of the proposed CNN and subsequently generates a new network according to the declared desired dimension. That means that efficient computing tool greatly simplifies the design and generation of the CNN through a short process, which just requires the declaration of the desired network dimension, the range of the local interaction, as well as the selected local behavior which are some elements that are going to be presented below. In addition to that, in order to prove the effectiveness and the robustness of both the methodology and the CNN model in real world data, an experimental test of a generated 10×10 network is made through the utilization of a distributed high accuracy analog temperature sensors network. The constraint that ought to be taken into consideration refers to the nature of the sensors that could accompany the proposed CNN, which must be analog (direct cell connection), or digital via the utilization of a digital-to-analog converter (indirect cell connection). An additional limitation that has to be taken into account as far as the proposed CNN network is concerned, involves the maximum input voltage allowed. Due to the utilization of the TL084CP Operational Amplifier model as a basic structural unit of the CNN, each one of the available cell input voltages (and therefore each one of the sensors output) should not exceed the barrier of ±15 V. The selected sensor model that satisfies all the above requirements is the low voltage analog temperature sensor TMP36. In this test, the final goal is to maintain the temperature parameter within the desired levels, so as to ensure the global stability and the proper function of the system.

The paper is organized as follows: in Section 2, all the necessary background on cellular neural networks is provided. Section 3 presents a CNN implementation approach based on the utilization of operational amplifiers. The proposed design automation methodology of CNNs lies in Section 4, whereas in Section 5, the experimental test and its corresponding results are thoroughly described. In the end, the conclusions drawn and future work are presented in Section 6.

2. Cellular neural networks

The cellular neural network (CNN) model which was proposed by Chua [27] from University of California at Berkeley as a practical circuit alternative to Hopfield [36,37] and other type of recurrent networks, involves an attractive parallel computational structure, particularly from the perspective of implementation in various micro and nanoelectronic technologies. The CNN paradigm includes cellular automata (CAs) [24] as a particular case and in addition it borrows many ideas and techniques from the field of Neural Computation. Computation in CNNs is brain-like rather than "classic" in the sense of the widespread computing architectures based on microprocessors. Unlike CAs which are mostly used to prove various theories or to model physical processes [38,39], CNN was intended from the beginning to be also a useful signal processing paradigm.

Due to the great number and variety of available architectures, it is relatively difficult for a strict CNN definition to be synthesized. As far as circuit topology is concerned, CNNs are systems that comprise from a finite set of locally interconnected non linear and often identical structural units. These entities, which include one single output and multiple inputs, are named as "Neurons", or "Cells". Mathematically, the cell entity can be modeled by a non linear system that utilizes the incoming data, its initial condition and other parameters in order to create its output [27,39].

There is a great difference between cellular and classic computation. Suppose an array of memory cells (i.e. a Random Access Memory). In a classic computer, the cells are sequentially updated and located by the central processing unit via some external buses while in a cellular computer each memory cell exchanges information locally only with the neighboring cells. A "gene" associated with each cell controls the exchange of information with the cells in a neighborhood. The cells are updated in parallel and there is no central processing unit to control the cells. Like in a classical computer, the array of cells starts from an initial state, which contains the problem, and the solution will be found in the same array of cells after a period of time during which computation emerges. While the designer of a classic computer focuses on the central processing unit, on data coding, address buses and instruction sets, the designer of a cellular computer has to focus mostly on the cell. The "program" is now coded in what Leon Chua called "cells' gene" (i.e. the entire set of parameters defining the cell). Quite often all cells have identical structure and parameters and various tasks can be "programmed" on the same CNN chip by simply changing the genes [40].

Next, a more specific and formal definition of the CNN model is going to be presented by referencing some of its basic descriptive mathematical equations. As it is already aforementioned, the basic structural unit of the CNN is the *cell*. The cell circuit is usually a set of both linear and non linear elements, such as resistors, capacitors, vccs (voltage controlled current sources) and independent sources. Although CNN architecture can be extended into three dimensional spaces, for simplicity reasons the case of a two dimensional circuit is currently studied. A paradigm of a 4×4 network is depicted in Fig. 1. A standard CNN architecture consists of an $M \times N$ rectangular array of cells $C(i, j)$, where i and j are the corresponding