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System-on-chip design of the cortical-diencephalic centre of the lower urinary tract

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ABSTRACT

This article presents the design of a field programmable gate array (FPGA)-based prototype of a system on chip (SoC) capable of behaving as one of the nerve centres comprising the neuroregulatory system in humans: the cortical-diencephalic nerve centre. The neuroregulatory system is a complex nerve system consisting of a heterogeneous group of nerve centres. These centres are distributed throughout the length of the spinal cord, are autonomous, communicate via interneurons, and govern and regulate the behaviour of multiple organs and systems in the human body. As a result of years of study of the functioning and composition of the neuroregulatory system of the lower urinary tract (LUT), the centres that regulate this system have been isolated. The objective of this study is to understand the individual functioning of each centre in order to create a general model of the neuroregulatory system that is capable of operating at the level of the actual nerve centre. This model represents an advancement of the current black box models that do not allow for isolated or independent treatment of system dysfunction. In this study, we re-visit our research into the viability of the hardware design of one of these centres—the cortical-diencephalic centre. We describe this hardware because functioning of the centre is completely configurable and programmable, which validates the design for other centres that comprise the neuroregulatory system. In this document, we succinctly present the formal model of the centre, propose a hardware design and an FPGA-based prototype, construct a testing and simulation environment to evaluate it and, lastly, analyse and contrast the results using data obtained from real patients, verifying that the functional behaviour fits that observed in humans.

1. Introduction

Researchers continually seek to resolve complex health problems with innovative methods. One strategy consists of combining technological and biological systems to resolve, monitor, correct, or modulate organ or bodily subsystems that, in one way or another, do not function as they should. Accordingly, the creation of embedded hardware devices that can be implanted into the body to correct its dysfunctions [1,2] is already achieving results [3–5].

The neuroregulatory system is one of the most sensitive and important elements of the human body. The system is extremely complex and, consequently, its proper functioning is difficult to study without causing it harm. Consequently, several studies that have addressed this subsystem and its malfunctions, such as (i) in Ref. [4], where the author describes the design and implementation of reconfigurable hardware with an architecture capable of emulating neural networks in real time for correcting potential disorders of the nervous system, and (ii) [3], which proposes the development of an emulator of the visual system to reproduce retinal and visual cortex neuron activity. In Ref. [5], the authors describe a proposal to implement hardware to improve speech in individuals with hearing impairments. Studies such as these explore the use of artificial systems for resolving problems that involve the neuroregulatory system. All of these reports demonstrate the difficulty in working with and understanding the nervous system and reveal that the root of multiple deficiencies in the body often lies in the nervous system, not in the malfunctioning organ.

After numerous years of study, we have now available a validated and confirmed theoretical model of the neuroregulatory system for the lower urinary tract (LUT) in both normal and abnormal conditions [6–18]. It was confirmed that, in all cases, and despite the fact that abnormal conditions were originally not taken into account in the model, the system behaves in a manner similar to actual biological

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systems [7]. The LUT was chosen due to social interest and its influence in the treatment of incontinence. Moreover, this system is sufficiently complex for rigorous validation of the model but simple enough to be able to be able to be modelled properly. The model was conceived and expressed using agent theory as a Multi-Agent System (MAS), being composed of agents capable of emulating the behaviour of different nerve centres that comprise it, and following a perceive-deliberate-execute paradigm (PDE agents) [8]. In the proposed model, each agent models a nerve centre, and communication between the agents models neuronal connections. The resulting model facilitates modular development, as it is already composed of independent, self-contained elements. This characteristic allows for the incorporation of system components without needing to considerably alter the remaining entities.

Until now, the primary achieved goals can be summarised as lower urinary tract monitoring and simulation, allowing physicians to identify the dysfunctions in their patients and allowing patients to train themselves through feedback to recuperate or substitute elements of their lost functionality. The next steps are to develop hardware designs based on a proposed architecture that implements the functionality of the neuroregulatory system. The hardware design can be converted into the bases of an embedded system on chip (SoC), which implements the functionality of neuroregulatory centres. In the present study, we focus on the hardware design of a specific centre, the cortical-diencephalic (CD) nerve centre. This centre forms part of the LUT, consisting of a known model for which sufficient information is available for appropriate validation using previously obtained patient data from different clinical techniques such as electromyography and pressure tests [6–8]. At the same time, the proposed design was conceived so that, in the near future, it could behave as any other nerve centre via simple modulation of its functional parameters.

With these objectives in mind, the remainder of this study will be structured as follows: section 2 provides a technical overview of the studies with major relevance to our current project; section 3 shows the proposed solution alongside the theoretical basis that precedes it, along with details of the prototype; section 4 presents the results of the tests and validations by comparing the proposed prototype with clinical data; and lastly, section 5 summarises the primary conclusions drawn from the study and provides suggestions for future work.

2. Technical overview

One of the most important challenges in medicine is improving the quality of life of patients struggling with some form of pathology caused by malfunctions in organs or other parts of the body that cannot be efficiently treated with traditional medicine. The synergy between medicine and technology [2] has been vital in resolving, monitoring, or correcting organ dysfunctions or damaged body systems. One potential solution consists of the creation of hardware that can be implanted in humans and compensate for these malfunctions. One objective for hardware used in the development of bioinspired systems is the creation of robust devices that can reliably replace organ functions [19–22].

The first step in constructing hardware systems is a complete understanding of the system to be developed. Consequently, numerous proposals emulate modelled biological systems [4], observe its behaviour [24] and, subsequently, aim to synthetically reproduce the behaviour of the biological system [23,37]. Once the system is understood, proposals of varying degrees of complexity can be developed, such as in Ref. [25], where the authors propose the design of a cortical neuroprosthesis capable of producing stimulating currents. In Ref. [26], the authors utilise neural networks implemented in reconfigurable hardware (FPGA – Field Programmable Gate Array) for stage segmentation, and in Ref. [27], the visual system is modelled to reproduce neuronal activity. The work in Ref. [38] implements a hardware system tolerant of errors from the study of prokaryotic bacteria morphology and behaviour, and a cellular machine is created in Ref. [41] by modelling the behaviour of the physarum polycephalum mould.

In creating a prototype, FPGA is useful because of its versatility and capacity to synthesise hardware. A wide variety of studies have made use of this technology for different projects, such as (i) a description of tools for the automatic design of visual system models [28]; (ii) a proposal of a hardware platform to study and experiment on of different processing schemes for visual information from artificial retinas [29]; (iii) the design of bioinspired circuits for real-time vision [30,45]; or (iv) investigating the resolution of auditory dysfunctions [31,32].

The use of FPGA to implement theoretical or mathematical models has been well accepted by the scientific community. Different studies have implemented FPGA for a number of different techniques, such as the following: (i) a highly efficient architecture to eliminate the negative effects of glasses [33]; (ii) the reconfigurable hardware implementation of an algorithm for facial detection [34]; (iii) modelling portions of the cerebral cortex to solve partitioning problems in processing sensory information [39]; (iv) the proposal of a processing unit by way of a neuronal model with optimised architecture [40]; and (v) a number of studies that implement algorithms to describe the functioning of neuronal networks [35,36].

These studies illustrate that FPGA is highly flexible in creating prototypes, assisting with designing tasks; enabling the exploration of alternatives to the original design; and providing support by way of parallelisation, processing speed, and the potential for high-density components, among other properties.

The model of the neuroregulatory system that is the focus of this study has been validated and confirmed by studying the LUT. The study of urinary dysfunctions is a complex problem that requires understanding not only the functional organs but also those involved in urinary function regulation [42] as well as the neuronal connections involved in urination. Investigating the neuroregulatory side of this issue [43], describes cases of incontinence caused by problems with nerve centres and explains how afferent signals act on these centres. These studies focus on the analysis and understanding of the LUT neuroregulatory system and its link with urinary incontinence, clearly demonstrating that the detection of possible dysfunctions, as well as correcting them, are an open problem. Consequently, studies such as [44] have described the development of an embedded system using the self-organisation of artificial neural networks to aid in the diagnosis of urinal dysfunction. From these studies, it can be concluded that projects focused on the LUT neuroregulatory system, few though there are, provide a better understanding of the functioning of this complex system. At the same time, problems arise from improper functioning of the neuroregulatory system that regulates the LUT. It is at this level that our study begins, i.e., in the appropriate neuroregulatory system and resolving a dysfunction that can be localised to a particular neuronal system.

3. History

Our group has been working on modelling and simulating the neuroregulatory system for over a decade, with the goal of contributing to its diagnosis [9], control, and possible correction of dysfunctions [6,10,11]. These studies provide the formal framework on which we construct our current design. In this section, we describe the most prominent aspects of this design.

According to the model shown in Ref. [6], a neuroregulatory biological system (NBS) is formed from a mechanical system (MS), a neuroregulatory system (NRS), neuronal connections (NC), and a system domain (SD). Formally, it can be defined as follows:

$$\mathrm{NBS} = \langle\, \mathrm{MS}, \mathrm{NRS}, \mathrm{NC}, \mathrm{SD} \,\rangle \tag{1}$$

From this point forward, we discuss only analyses of the neuroregulatory systems (NRS), its neuronal connections (NC), and the system domain (SD), as these are the elements involved in our current study.

Let A and B be ensembles that represent two types of system components. A neuronal connection between an element x from A to an