Hardware Design of the Cortical-Diencephalic Neuroregulatory Center of the Lower Urinary Tract

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Abstract: The neuroregulatory system in humans, governs and regulates the behavior of their organs and systems. This system is composed of a set of neuronal centers, distributed along the spinal cord, which operate independently, along with their interconnections nerve. In previous research, through the study of the functioning and composition of the neuroregulatory system of the lower urinary tract, we have been able to isolate the centers involved in this function with the objective of understanding their individual operation and be able to create as well a general model of neuroregulatory system capable of operating at the level of neuronal center. The long-term objective of the research is the development of a system on chip (SoC) capable of behaving as a fully programmable neuroregulatory system. In this paper we take the next step in the research studying the feasibility of the hardware design of one of these centers neuroregulatory, in particular the center Cortical-Diencephalic, achieving a first prototype and architectural proposal. To do this, it has been isolated the behavior of this center, has proposed a design hardware implemented on FPGA to create a prototype, has been constructed a simulation environment for your evaluation and, finally, the results have been analyzed, verifying that their functional behavior is set to the expected in a human being and that operational requirements necessary for their implementation are technical and architecturally feasible.

Keywords: Neuroregulatory system, Hardware design, FPGA, Cortical-Diencephalic center

1 Introduction

At present we find ourselves with a multitude of pathologies, where innovative solutions are adopted in the used technological systems through which can be resolved, monitor, or correct the dysfunctions of modular components or subsystems of the human organism that for some reason do not shown a correct behavior. In this

line, which is one of the strategies that it takes to give solution to such problems is the creation of embedded hardware devices that can be implanted in humans to correct its dysfunctions [Mead, 90][Indiveri and Horiuchi, 11], a strategy that already shows encouraging results for a wide range of problems [Junjie, 05][Moore et al., 12][Martínez et al., 05].

Within the human body, one of the most complex and sensitive systems is that of the neuroregulatory system. This is due to the fact that its operation is not yet fully understood and the difficulty to study when it is working without cause damage. In spite of this, there are papers that approach this subsystem and its dysfunctions, such as for example [Moore et al., 12] where the author describes the design and implementation in reconfigurable hardware architecture capable of emulating cellular neural networks in real time to correct possible disorders in the nervous system, or in [Kawasetsu et al., 14] where it is proposed the development of an emulator of the visual system for the reproduction of neural activities in the retina and visual cortex. These papers are just a few examples that explores the use of artificial systems in the resolution of problems of the biological neuroregulatory system. Papers such as these show the great complexity for working with the nervous system, his understanding and that the root of a multitude of problems the agency frequently lies in the nervous system and not in the organ in question that presents the dysfunction.

During the last few years, our research has focused on the study of neuroregulatory system (NRS) human and in the possibility of building artificial systems capable of simulating its behavior. Now we have a complete model of the NRS able to reproduce the operation of the biological system [Soriano, 01]. The model has been expressed through a multi-agent system (MAS) composed of agents capable of emulating the behavior of the various nerve centers that form, perceiving, deliberating and executing [Ruiz et al., 04]. Each agent component is a self-contained and independent of the rest, like the human nerve centers, which facilitates the construction of a system specifying the functionalities of each center and adding it without significantly changing the rest of the system. To validate the proposed model has been applied to the neuroregulatory system lower urinary tract (LUT) [García et al., 03]. This subsystem is complex enough to exhibit the nature of the neuroregulatory system but, at the same time, it is accessible enough to be able to study how the centers to make up, the operation of each one of them and the signals that are involved in its operation. This study has enabled us to verify that the proposed model could be materialized into one of the subsystems of the real body and the operation displayed was similar to the real, even in the case of a malfunction that originally had not been contemplated. Finally we have conceived a software tool through which you could see the simulation of the neuroregulatory system, in particular the LUT, defined by the model [García et al., 02a].

After the theoretical study, modeling, validation and simulation software, the next step is moving toward the materialization of a physical hardware to achieve a first prototype and architectural proposal that implements the functionality of the neuroregulatory. This prototype hardware can become the germ of a system embedded SoC (System on Chip), in such a way that we are able to produce chips in which implements the functionality of neuroregulatory centers or even a neuroregulatory complete, for example of the LUT. This paper focuses on the theoretical model of the center Cortical-Diencephalic (CD), one of the centers that has

been modeled within the formal framework of the neuroregulatory system of the LUT and that later will be detailed its operation.

For the development of the research, the work has been divided into the following sections: section 2 contains a state of the art on the papers of greater relevance related with the proposal; in section 3 we discuss the basis of the background that precede the proposal; in section 4 we will show you our proposal for a solution together with the implementation details of the hardware and prototyping center CD; in section 5 we present the results of the tests and validations from comparisons between the proposed prototype and the biological system; finally, section 6 highlights the major findings sloughed off of the paper and proposals for future work.

2 Related Work

In the field of medicine there are numerous pathologies that are caused by the malfunction of components or subsystems of the body and from the traditional medicine cannot be resolved in a way totally efficient. The synergy between technology and medicine [Mead, 90] has been a fundamental step to resolve, monitor or correct the dysfunctions of components or subsystems of the organism that has been damaged, being one of the possible solutions to this problem the creation of hardware devices that can be implanted in human beings to remedy this malfunction. One of the reasons for which makes use of the hardware for the development of bio-inspired systems is to achieve robust devices that might supplant almost infallible organic functions [Chicca et al., 14] [Flaherty et al., 10] [Moffitt et al., 10]. The first step in the construction of hardware systems is the full compression of the system to meet, it is for this reason that multitude of proposals made by the emulation of the biological system modeling [Moore et al., 12] watching their behavior [Jan et al., 06], and chasing in the first instance attain reproduce the behavior of the biological system on a synthetic system [Corradi et al., 14]. Once you have reached the compression of the system may develop proposals for diverse stalled, as [Romero et al., 05] where the design of a cortical neuroprosthesis capable of producing flows of neurostimulation; [Girau and Torres-Huitzil, 07] where are used neural networks implemented on FPGA for the segmentation of scenes or in [Kawasetsu, 14] where emulates the visual system for the reproduction of neuronal activity. The inspiration to create hardware can even come from outside of the man himself, as is the case of [Samie et al., 13] where there is an implementation of a system fault-tolerant hardware from the study of the morphology and behavior of prokaryotic bacteria, or [Tsompanas and Sirakoulis, 12] where plans to the creation of a cellular automaton from modeling the behavior of the mold physarum polycephalum. Learn about the system in depth allows you to reproduce your behavior, whatever this system.

Large number of jobs related to the creation of hardware have made use of FPGA reconfigurable hardware or due to its versatility and ability to synthesize hardware in proposals of all kinds: make the description of tools for the automatic design of the models of visual processing [Martínez et al., 05]; propose a hardware platform that can be used for the study of and experimentation with different schemes of processing of visual information based on artificial retinas [Martínez et al., 02]; describe the design of circuits for bio-inspired real-time vision [Mota, 08]; or the work related to the resolution of auditory dysfunction [Meza-Escobar et al., 08] [Junjie, 05] [Leong

and Jin, 03]. The use of reconfigurable hardware to implement theoretical or mathematical models [Osio et al., 06] also is one of the hottest topics addressed by the scientific community. You can see works by this court in thousands of proposals such as: a high-efficiency architecture to eliminate negative effects caused by the lenses [Zicari, 13]; the implementation in reconfigurable hardware of an algorithm for the detection of faces [Meng, 06]; the inspiration in cortical areas of the brain to solve problems of the partition of the processing of sensory information [Rodriguez et al., 13]; propose a processing unit from a neural model, optimizing its architecture [Fiack et al., 15]; as well as jobs that implement algorithms that describe the operation of the neural networks [Dinu et al., 10] [Ji et al., 15]. These papers can be seen that the FPGA possess a great deal of flexibility to create prototypes, facilitating the work of the designer and the possibility of exploration of alternatives to the original design, based on properties such as parallelism, high-speed processing and its possibility of high component density.

In our study of the human neuroregulatory system we have achieved a model that has been validated through the study of the lower urinary tract. The study of the urinary tract dysfunction is a complex problem with that can not only be fixed point of attention on the functional bodies but there are also regulatory bodies [Kinder et al., 99], raising the neural connections that are involved in the process of micturition. Progress in the study of the part neuroregulatory, in [Morrison et al., 05] describes problems with incontinence caused by some neural center and explains how they operate the signals on the afferent neural centers. These studies are focused on the analysis and understanding of the neuroregulatory system of the LUT and its link with the problems of urinary incontinence, clearly showing that the detection of possible dysfunctions as well as its related fix the system neuroregulatory are open issues. In this line already starting to see some proposals as [Gil et al., 07] which describes the development of an embedded system based on the self-organization of artificial neural networks for the aid in the medical diagnosis of urinary tract dysfunctions. Of all these studies it can be concluded that the work focused on the neuroregulatory system are few although already allow us to better understand the operation of this complex system, and that there are problems which are derived from a malfunction of the neuroregulatory system which manages, and this is where our proposal affects, in the own neuroregulatory system and provide a solution when the failure occurs in the neuronal system itself.

3 Background

In the last decade we have worked in research concerning the human neuroregulatory system, creating a model based on the theory of agents who is able to express the behavior of this distributed system. For testing and validation we focus on the study of the neuroregulatory system of the Lower Urinary Tract, specifically the modeling and simulation, both of the mechanical system as neuroregulatory system, in order to contribute to the diagnosis [Méndez, 08], control of biological systems and possible correction of its dysfunctions [Payá et al., 13] [Soriano, 01] [García et al., 02a]. These previous research provide the formal framework on which they are constructed the current proposal by what will briefly describe the most salient aspects of the same.

The model of the LUT divides the system into two separate parts: the mechanical and neurological. The first part describes the biomechanics of the LUT and is related to the anatomy and physiology of the constituent elements [Groat, 06] [Yucel and Baskin, 04]. The second part is related to the anatomy and physiology of the neural control of the urinary tract, transmission centers and areas that are responsible for facilitating and inhibiting the process of micturition [Bortolini et al., 14] [Fowler et al., 08][Payá et al., 13]. This second part is the one that will be of interest to the proposal, especially the mathematical model obtained.

The model of the neuroregulatory system describes the behavior of the neuronal connections and the control centers of the nerves involved in the LUT [Soriano, 01] [Ruiz, 03] [García et al., 03] [García et al., 02b] [Fernández and Payá, 05]. The neuronal centers are groups of neurons with the same function located along the spinal cord [Soriano, 01] [Ruiz, 03], which receive signals generated by the mechanical system and other centers, the processed and relayed to other centers or toward the mechanical system [Soriano, 01] [García et al., 03] [Ruiz et al., 04] [García et al., 02]. The interaction with the mechanical system is done through a set of neural signals efferent and afferent. The neural pathways carry information generated by the mechanical system toward the control centers, these later processed and transmitted to the mechanical system acting as well on certain areas of the system.

Figure 1(a) shows how the set of control centers related to the LUT is distributed by the coccyx and spine, and as the neural pathways connect each of the centers with bodies or other centers with which it interacts. After studying the biological scheme could obtain a conceptual model, figure 1(b), with whom he could realize the centers involved, their connections and the signals involved in the process of regulating LUT [Soriano, 01][Gil et al., 11]. Signals present in the LUT system are considered to be of type: afferents (A) when they come of the mechanical system; internal (I) when they are generated by the voluntarily areas facilitators of the retention and micturition, or in conjunction with all the internal signals that transmit impulses system from a control center to another; and finally, efferent (E) that act on the muscles of the mechanical system. For the sake of clarity, all the signals are appointed by the letters A, E, I to indicate the type along with a superscript that indicates the source of the signal, and a subscript that indicates the target, for example the ${}^{PM}I_{DGC}$ signal indicates it is a type of internal signal that goes from the center of Pontine Micturition (PM) until the center of the Dorsal Grey Commissure (DGC).

Voluntary signals described are (I) because, although they are external to the neuroregulatory system, are signals which come from other neural centers of other subsystems neuroregulatorys, in this case ${}^{M}I_{CD}$ and ${}^{R}I_{CD}$. These two signals are generated by the voluntary areas to conscious level and will depend on internal factors, such as the wish or not to initiate micturition, and external factors, such as if the person is in an environment conducive to initiate micturition, if you hear a flow of water and so on. The ${}^{R}I_{CD}$ signal will be activated at the time that the individual feels the first sensations of fullness but you want to continue in the storage phase and the signal ${}^{M}I_{CD}$ is activated during a short interval of time and trigger the start of micturition.

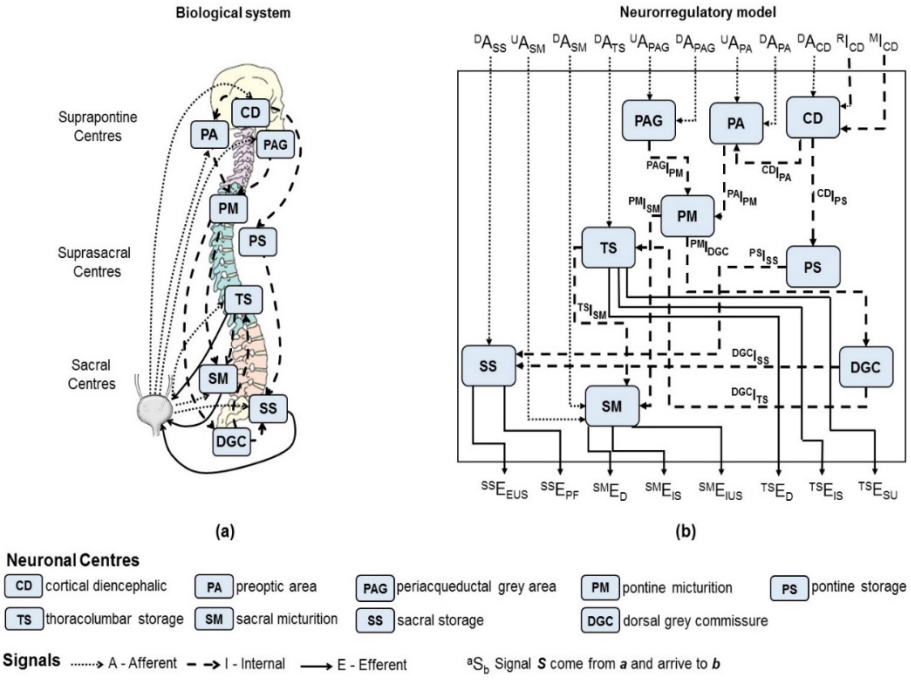

Figure 1: a) Biological scheme from the LUT centres and its connections b) The LUT system model and the signals that are involved

Of the neuronal centers that make up the LUT, the highest level and that is going to concentrate the proposal of the work is the center Cortical-Diencephalic (CD). This center is associated with the areas facilitators and inhibitors of the micturition [Soriano, 01] [García et al., 02b] [Méndez, 08]. Another feature that presents the center CD, and that highlights its importance in the functioning of the system as a whole, is to monitor the areas of voluntary micturition, the areas of voluntary retention and the mechanical system to respond properly to the changes, as well as start the process of micturition unintentionally and take appropriate action according to the current state of the system and therefore depends on the pressure of the detrusor muscle ($^{D}A_{CD}$) of the internal signal facilitator of micturition ($^{M}I_{CD}$) and internal signal activating the retention ($^{R}I_{CD}$). Depending on the input signals, this center can activate the output $^{CD}I_{PA}$ which is the internal signal that goes from the center CD toward the center of the preoptic area (PA) or activate the $^{CD}I_{PS}$ signal that is the signal that goes from the center CD to the center of pontine storage (PS). In figure 1 (b) may be seen the inputs and outputs associated with the center, these do not alter directly the state of the system, but if that acts on other centers (PA and PS) with its neural signals $^{CD}I_{PA}$ and $^{CD}I_{PS}$.

The concept of neuronal center as a set of neurons that processes signals and produces answers was modeling, because of its similarity with an agent PDE (Perception, Deliberation, Execution). Therefore, the neuroregulatory centers, and among them the center CD, have been modeled on the basis of a architecture of an

agent PDE, adding also the capacity to memorize, which allows you to have a deliberative process more powerful and rich [Ruiz et al., 05][Ferber, 99].

From general model [Soriano, 01] [García et al., 02b] [Méndez, 08] defines the structure that represents the center with the expression:

$$CD = (\Phi_{CD}, S_{CD}, Percept_{CD}, Mem_{CD}, Decision_{CD}, Exec_{CD}) \quad (1)$$

Where Φ_{CD} corresponds to the set of perceptions, S_{CD} corresponds to the set of internal states, $Percept_{CD}$ provides information on the status of the system to the center, Mem_{CD} center allows you to display the awareness of the current state, $Decision_{CD}$ selects the next action of the center and $Exec_{CD}$ represents the intention of the center to act on the system [Soriano, 01].

For the CD center that is still under study, the function of perception ($Percept_{CD}$) provides a sublist of signals where the center CD is origin or destination, or, which selects all the signals both input and output that are involved in the implementation of the center CD. This function depends on the set of signals afferents (ANS) sent by the mechanical system and efferent neural signals (ENS) sent to the mechanical system related to the center. Therefore, these sets are specified as:

$$ANS_{CD} = \{{}^{D}A_{CD}\} \quad (2)$$

$$ENS_{CD} = \{\ \} \quad (3)$$

On the other hand, the internal state of the center is formed by those neural signals in which the center is the origin or destination, or is internal signals of entry (INS^{I}) and output (INS^{O}), which are defined as.

$$INS^{I}_{CD} = \{{}^{M}I_{CD}, {}^{R}I_{CD}\} \quad (4)$$

$$INS^{O}_{CD} = \{{}^{CD}I_{PA}, {}^{CD}I_{PS}\} \quad (5)$$

To facilitate the management of this list of signals has been defined a translation operation (T_{CD}). After selecting the signals of the world intervening invokes the function of translation that is located within the process of perception and that associates the internal state of the center with the different segments of the curve of bladder pressure, identified by the different phases of the system [García et al., 02]. The function of translation in that center is defined as.

$$T_{CD}(\varphi, s) = \begin{cases} E\_I & \text{if } (\varphi.{}^{D}A_{CD} < {}^{D}H_{CD1}) \wedge \neg s.{}^{M}I_{CD} \wedge \neg s.{}^{R}I_{CD} \\ E\_R & \text{if } ({}^{D}H_{CD1} \leq \varphi.{}^{D}A_{CD} < {}^{D}H_{CD2}) \wedge \neg s.{}^{M}I_{CD} \wedge s.{}^{R}I_{CD} \\ E\_M & \text{if } (({}^{D}H_{CD1} \leq \varphi.{}^{D}A_{CD} < {}^{D}H_{CD2}) \wedge s.{}^{M}I_{CD} \wedge \neg s.{}^{R}I_{CD}) \\ & \quad \vee (\varphi.{}^{D}A_{CD} \geq {}^{D}H_{CD2}) \end{cases} \quad (6)$$

Where E_I is the inactive state, the center is in a state that does not provide any activity, this state is reached when the signal ${}^{D}A_{CD}$ is less than the threshold ${}^{D}H_{CD1}$ and the internal signals ${}^{M}I_{CD}$ and ${}^{R}I_{CD}$ are not enabled. It is the E_R retention state, this state is achieved when the signal ${}^{D}A_{CD}$ is greater than or equal to the threshold ${}^{D}H_{CD1}$ and less than the threshold ${}^{D}H_{CD2}$, the internal signal ${}^{M}I_{CD}$, is not enabled and the voluntary retention signal ${}^{R}I_{CD}$ if enabled. Finally E_M is the state of

urination, to this state is reached when any of the following circumstances: a voluntary urination if the signal ${}^{D}A_{CD}$ is greater than or equal to the threshold ${}^{D}H_{CD1}$ and less than the threshold ${}^{D}H_{CD2}$, the internal signal ${}^{R}I_{CD}$ is not enabled and if the signal is active for the beginning of urination ${}^{M}I_{CD}$; a second case, involuntary urination in the case that the signal ${}^{D}A_{CD}$ exceeds the threshold ${}^{D}H_{CD2}$. From the current state of the center and what are you seeing the same you can change to a new state and decide what action run.

The values of the thresholds ${}^{D}H_{CD1}$ and ${}^{D}H_{CD2}$ were determined empirically during the construction of the theoretical model of the LUT. These thresholds configured the sensitivity of the center CD to the pressure of the detrusor ${}^{D}A_{CD}$, of way that make the center CD react to stresses of detrusor higher or lower. Or, move within certain ranges of a few, but its specific value depends on each individual.

For its part, the role of decision ($Decision_{CD}$) will act as follows:

$$\text{Decision}(\varphi, s) = \begin{cases} \text{Setsignalvalue}(\text{FunD}_{CD}(\varphi, s)) \text{ if PreD}(\varphi, s) \text{ verified} \\ \gamma_{\varphi} \text{ if not checked} \end{cases} \quad (7)$$

The function of decision ($Decision_{CD}$) relates an action with the perception ($Percept_{CD}$) of a particular internal state of a center. Basically is to set the value of a set of output signals. Has a structure that depends on its internal functions: the function of precondition ($PreD_{CD}$) and the role of decision ($FunD_{CD}$).

As well as the function of decision, the function of memorization (Mem_{CD}) also presents a general structure which depends on their internal functions: the function of precondition ($PreM_{CD}$) and memory ($FunM_{CD}$). In the case of the function of precondition, returns false only if the signal ${}^{D}A_{CD}$ is less than the threshold ${}^{D}H_{CD1}$, the internal signals ${}^{M}I_{CD}$ and ${}^{R}I_{CD}$ are not activated and the translation function returns as a result the state of inactivity or micturition, returning true in any other case. For its part, the internal function of memorization $FunM_{CD}$ is responsible for modifying the internal signals input ${}^{M}I_{CD}$, ${}^{R}I_{CD}$ and internal signals output ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$. This feature will assign the value 0 to all the internal signals both input and output signal when the ${}^{D}A_{CD}$ is less than the threshold ${}^{D}H_{CD1}$, the internal signals ${}^{M}I_{CD}$ and ${}^{R}I_{CD}$ are not activated and the translation function returns as a result the state of inactivity or micturition. You can also activate the signal ${}^{CD}I_{PA}$ putting its value to 1 and leaving with value 0 to the signal ${}^{CD}I_{PS}$, this occurs when the signal ${}^{D}A_{CD}$ is greater than or equal to the threshold ${}^{D}H_{CD1}$ and less than the threshold ${}^{D}H_{CD2}$, the internal signal ${}^{M}I_{CD}$ is active, the ${}^{R}I_{CD}$ signal is not active and the translation function returns as a result the state retention or micturition. In general have been explained the cases that are reflected in the definition of memory function shown below.

$$\text{PreM}_{CD}(\varphi, s) = \begin{cases} \text{False if } (\varphi.{}^{D}A_{CD} < {}^{D}H_{CD1}) \wedge \neg s.{}^{M}I_{CD} \wedge \neg s.{}^{R}I_{CD} \\ \qquad \wedge T_{CD}(\varphi(t), s(t)) = I, M \\ \text{True if not checked} \end{cases} \quad (8)$$

$$
\text{FunM}_{CD}\ (\varphi,\ s) = \begin{cases} < (s.^{M}I_{CD,}\ 0),\ (s.^{R}I_{CD,}\ 0),\ (s.^{CD}I_{PA,}\ 0),\ (s.^{CD}I_{PS,}\ 0) > \text{ if } (\varphi.^{D}A_{CD} < {}^{D}H_{CD1}) \wedge \neg\, s.^{M}I_{CD} \wedge \neg s.^{R}I_{CD} \wedge ts\ (t) = I,\ M \\ < (s.^{M}I_{CD,}\ 0),\ (s.^{R}I_{CD,}\ 1),\ (s.^{CD}I_{PA,}\ 0),\ (s.^{CD}I_{PS,}\ 1) > \text{ if } ({}^{D}H_{CD1} \leq \varphi.^{D}A_{CD} < {}^{D}H_{CD2}) \wedge \neg\, s.^{M}I_{CD} \wedge s.^{R}I_{CD} \wedge ts\ (t) = I,\ R \\ < (s.^{M}I_{CD,}\ 1),\ (s.^{R}I_{CD,}\ 0),\ (s.^{CD}I_{PA,}\ 1),\ (s.^{CD}I_{PS,}\ 0) > \text{ if } ({}^{D}H_{CD1} \leq \varphi.^{D}A_{CD} < {}^{D}H_{CD2}) \wedge s.^{M}I_{CD} \wedge \neg s.^{R}I_{CD} \wedge ts\ (t) = R,\ M \\ < (s.^{M}I_{CD,}\ val),\ (s.^{R}I_{CD,}\ val),\ (s.^{CD}I_{PA,}\ 1),\ (s.^{CD}I_{PS,}\ 0) > \text{ if } (\varphi.^{D}A_{CD} \geq {}^{D}H_{CD2}) \wedge ts\ (t) = R,\ M \wedge \forall val \in_{R} \end{cases} \tag{9}
$$

Where ts (t) = T_{CD} (φ (t), s (t)).

Finally, the function of execution (*Exec*$_{CD}$) allows you to perform the action selected in the function of decision.

It is important to remember that the whole exhibition presented in these background refers to the operation of the center CD in particular, if you want more information on the modeling of the general system should be used in the work and existing publications [Payá et al., 13] [Soriano, 01] [García et al., 02a] [García et al., 03] [Ruiz et al., 04], since by issues of space have been collected only the most important aspects to understand the proposal.

4 Proposal of prototype hardware in a neural center

Our proposal consists of a hardware design of the model of the center Cortical-Diencephalic (CD) studied. It has been chosen this center because it is one of the main centers are involved in the process of micturition, in addition to that is associated with the areas facilitators and inhibitory to micturition. Figure 2 shows an overview of the proposed design, whose main features are the following.

The center CD has three input signals ($^{D}A_{CD}$, $^{M}I_{CD}$ and $^{R}I_{CD}$) and two output signals ($^{CD}I_{PA}$ and $^{CD}I_{PS}$). As described above, the afferent signals (A) and efferent (E) of any center communicate with biological organs by which need to be digitized in the entry and later converted back to analog to its output. Likewise, the internal signals (I) will be digital signals. External signals, both input and output, must be adapted. For this we added two items to each one of them: a CAD or a CDA according to the signal is input or output respectively and a FIFO memory to ensure that relevant information is not lost.

Although in this work, both by understanding such as validation, the proposed center is the neuronal CD, the intention is to propose a generic architecture that neuronal center to carry out the functions that you suggest. For this reason it was incorporated into the design of a memory configuration that allows you to store the information that each center needs. As discussed in the previous paragraph, the thresholds to the that is carried out the operation of the center are values that were established empirically and that, therefore, because they may be different from a human being to another, we have considered who should also be able to be changeable within the configuration by what will also be included in this memory.

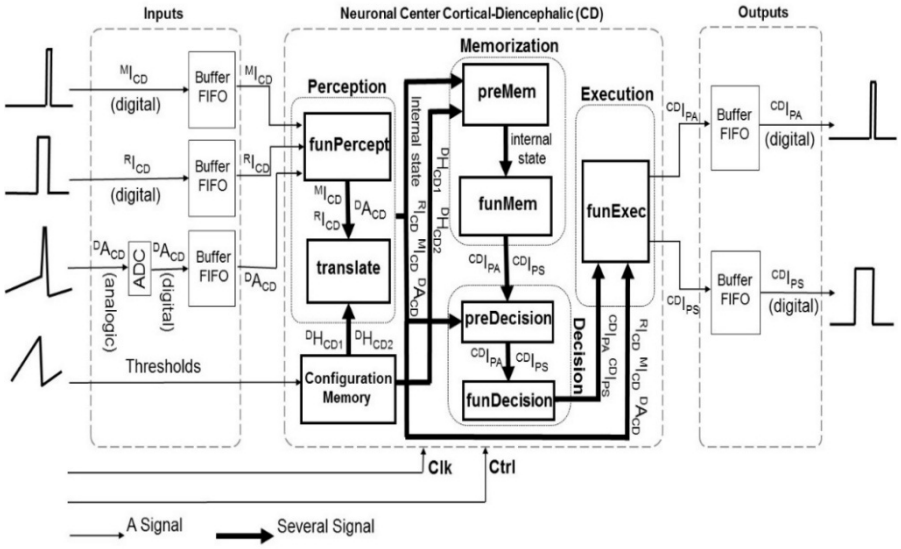

Figure 2: General scheme of hardware design of the CD center

The hardware system can be found in 3 different states of execution:

- Inactive: is not processed any input signal or it emits no result.
- In-memory data loading configuration: in this state the hardware is loading in their records and internal memory the information necessary to process signals, such as for example the thresholds necessary for making comparisons.
- Execution: in this state the hardware processes the input signals, using the values and internal configuration charged to generate output signals.

The control signal (*Ctrl*) will be responsible to indicate the state in which the system is located. The design also features a clock signal (*Clk*) to synchronize the activity of the system.

Following the general model of neuroregulatory center, the system is composed of the four major blocks hardware that implement the skills of *perception, memorization, decision* and *execution*, in which will be carried out the functionality of the system. The block of perception is composed of two functions: the function of perception in if (funPercept) that is responsible for selecting the input signals; and the function of translation (translate) that interprets these inputs and gets the current state of the system. The memorization block is composed of two functions: the function of pre-memorization (preMem) that is responsible for calculating a precondition that indicates whether it has or not to change the internal memory of the system; and the function of memorization (funMem) which is aimed at changing the internal memory of the center according to the result of preMem. The block of decision is divided into two functions: the function of pre-decision (preDecision) that calculates whether it has to perform or not the decision to be made; and the function of decision (funDecision) which is responsible for taking a decision depending on the entry. And finally the execution block which contains the function execution (funExec) that is

responsible for sending as response signals internal ${}^{CD}I_{PA}$, ${}^{CD}I_{PS}$ to other centers of the system. The following is a comprehensive description of each of the blocks.

4.1 Schematic of signals

Figure 3 shows the signals that are exchanged between the various modules that make up the hardware, its origin and destination, its nomenclature and the number of bits that compose it. This prototype has to implement in hardware the same functions that have been described in the modeling of the center and therefore involve a large number of variables that will be translated into signals of different dimension (1 bit or 16 bit).

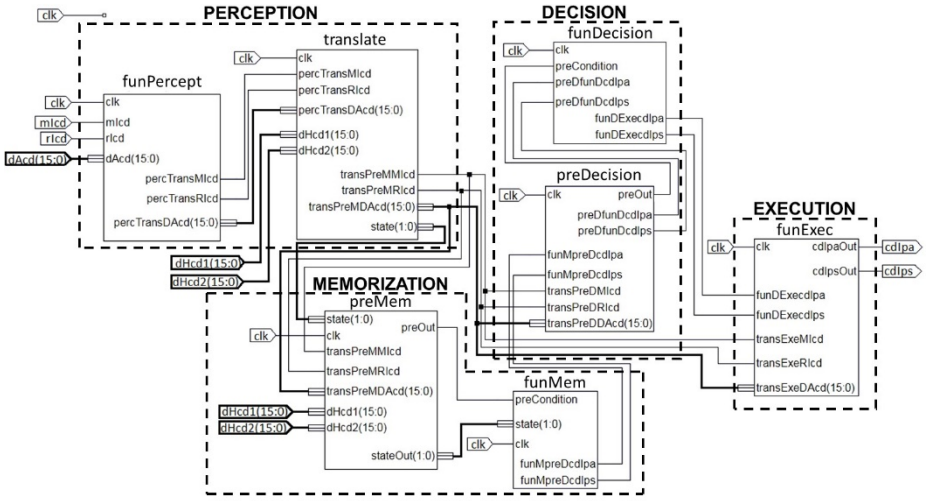

Figure 3: Hardware diagram from the model of the CD center

4.2 Function funPercept

The first step in the processing center of the CD is the acquisition of the signals from the environment that are involved in the execution of the center; funPercept performs the acquisition signals getting the ${}^{R}I_{CD}$, ${}^{M}I_{CD}$ and ${}^{D}A_{CD}$. In the case of signals I, these have as origin and other centers are neuroregulatorys of character inhibitor/activator, so only take two possible values 0/1. In the case of the signal source as ${}^{D}A_{CD}$ has the mechanical system and takes a numeric value that expresses the pressure of the detrusor muscle, which will be representing at the hardware level as a 16-bit signal. Figure 4 shows the diagram of this hardware functional block.

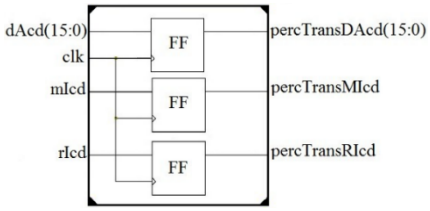

Figure 4: Design of the funPercept function

For this reason, the lines used for the signals I shall only 1 bit while the used to store the value of the signal of the detrusor muscle would be 16.

The module funPercept in this case it is trivial, since in reality does not exercise any function to implement a concrete expression of the center CD, but we consider it appropriate to include physically in the hardware already that in a future this function must be able to select from among all the signs of the world, those that are of interest to the center in processing. Although we are now interested in the implementation of the center CD, to extend below the hardware toward other control centers as the PA, PAG, PM…, where each one of them must be able to discern the signs of the world you are interested in.

4.3 Function translate

This function processes the signals perceived to produce a state of the system. As has been defined in formula (6), in addition to the acquired signals in the perception, this function makes use of the thresholds ${}^{D}H_{CD1}$ and ${}^{D}H_{CD2}$, values which have been previously stored in the configuration memory during the loading phase of memory, to produce a status (*state*). The translate function compares the value perceived by the pressure of the detrusor ${}^{D}A_{CD}$ (16-bit signal) with the thresholds stored in memory (16-bit values also), and the value of the internal signals perceived (signals of 1 bit type inhibitor/activator) in the previous function. The state of the system obtained shall be decisive for the subsequent blocks of memorization and decision. For the center CD the possible states of the system are inactive, retention or micturition, for what will be used a line of 2 bits where is stored the state. Figure 5 shows the internal diagram of the translate function.

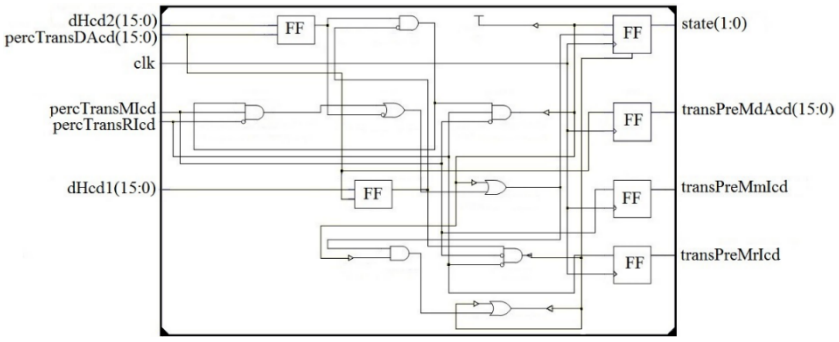

Figure 5: Design of the translate function

The overall result of the block perception therefore is to be determined by the value of the calculated status (*state*) over the signals received in the role funPercept ($^{R}I_{CD}$, $^{M}I_{CD}$ and $^{D}A_{CD}$).

4.4 Function preMem

Within the memorization process of the center CD there are two functions that are responsible for carrying out the process. One of them is the function of preMem whose operation involves the use of threshold values $^{D}H_{CD1}$ and $^{D}H_{CD2}$, which are two 16-bit signals, and all signals produced by the translate function. Once you receive all the signals, there are a group of operations based on logic gates and records of type flip-flop, to obtain as a result the output signal of preOut 1 bit, since this signal can only take the values 0 or 1. This signal is very important for funMem, since depending on the value of preOut the funMem function assigns values to the internal signals of outlet in the center CD.

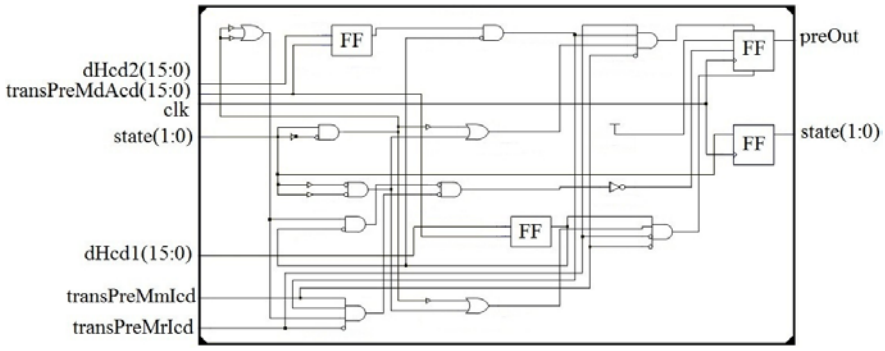

Figure 6: Design of the preMem function

This block produces two signals, *preOut* and *state*, which are sent to the next block.

4.5 Function funMem

This function is responsible for, from the state in which the system is located and the preOut signal received, enable or disable the output signals funMpreDcdIpa and funMpreDcdIps, which represent the internal signals $^{CD}I_{PA}$ and $^{CD}I_{PS}$ model respectively.

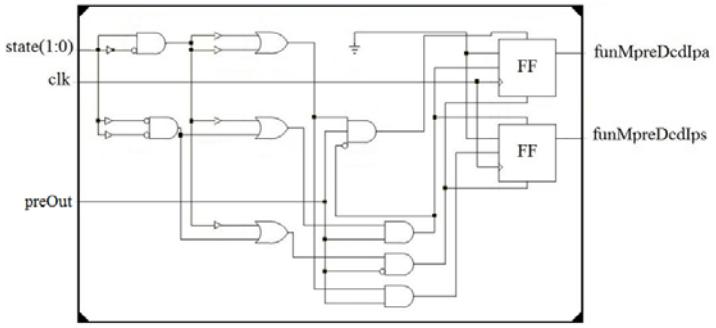

Figure 7: Design of the funMem function

The result of these output signals is the central objective of all the implementation of the center CD, but will have to go through a block Decision before being sent to another center neuroregulatory system.

4.6 Function preDecision

preDecision, next to the block funDecision, implements the function decision of the center CD. preDecision is responsible for producing and send a signal to indicate the possibility of taking a decision, i.e. will activate or deactivate the decision to execute the changes made to the internal signals ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$. Figure 8 shows the internal workings of this block.

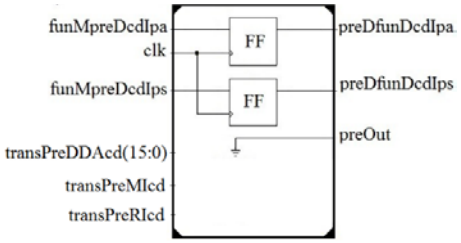

Figure 8: Design of the preDecision function

The signals it receives this block, funMpreDcdIpa and funMpreDcdIps, are defined by 1 bit each; the output internal signals ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$, as well as the condition signal preOut enable or disable the decision are also defined by 1 bit.

4.7 Function funDecision

The other function that is part of the decision process of the center CD is funDecision, responsible for making the decision as to whether it is executing or not the changes made to the internal signals ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$ and is implemented as shown in figure 9.

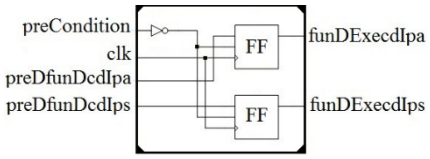

Figure 9: Design of the funDecision function

4.8 Function funExec

Finally, the model has the function execution of the physical layer is responsible for transmitting the signals produced by the circuit to the centers as appropriate. Figure 10 shows the design of this block.

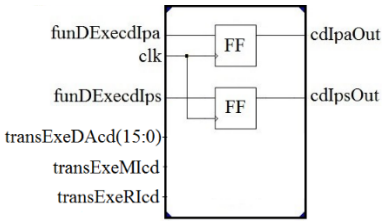

Figure 10: Design of the funExec function

5 Tests and Validation

To test and validate the proposed prototype hardware, it has been decided to carry out its implementation through the use of FPGA, thus avoiding having to physically build the circuit. When using this type of technologies raffle the possible errors that underlie the physical materialization of hardware such as a bad connection, a damaged component or sporadic errors resulting from incorrect voltages, obtaining a reconfigurable circuit completely equivalent. In this case we have made use of a plate model ZYBO Zynq FPGA-XC7Z010 since amply covers our needs.

To ensure that the proposed prototype complies with the desired biological functionality it has been designed a process for testing and validation divided into two stages, which, to be carried out, will use a subset of signals obtained during clinical trials conducted in the phases of modeling of the neuroregulatory system and that already were also used to validate the operation of the model of the LUT developed [Soriano, 01] [García et al., 02a].

In the first stage we will carry out the implementation in reconfigurable hardware center CD and we will submit the implementation to the simulation in isolation from its operation, using the set of signals. The expected result must match the behavior of the center CD that was obtained during the modeling.

In the second phase we use the simulator for the LUT developed in previous work [Soriano, 01] [García et al., 02a] and that was used to demonstrate the validity of the model. This software simulates the behavior of each and every one of the centers that form the neuroregulatory system of the LUT, following the model of multi-agent

system, and providing opportunity to observe the execution of the centers in detail. In this case and for the tests to perform, what it is proposed is to replace the center track CD simulated by the software implemented in FPGA, making the simulator communicates with the FGPA and use to this as if the center CD treated, so that the system software uses the hardware to process and get the signals that would correspond to the center CD. This way you can verify that the proposed system hardware is corresponds with the center CD equivalent software that has already been validated in previous works.

5.1 Design Synthesis hardware proposed

After the hardware description of each of the blocks that make up the design of the center CD done in the previous chapters, was carried out of the synthesis process where it was obtained an equivalent circuit implemented in FPGA, and that it possesses characteristics that shown in table 1.

Logic utilization	Used	Available	Utilization
Number of slice registers	49	35200	0%
Number of slice LUTs	74	17600	0%
Number of fully used slice LUT-FF pairs	6	117	5%
Number of bonded IOBs	53	100	53%

Table 1: Device utilization summary

For the generation of the hardware were used 49 records of 35200 available in the FPGA and 74 Look-Up Tables (LUTs) of 17600 available, with what is observed that the amount of resources used is minimal, important aspect since the Look-Up Tables are an essential element in the synthesis of logical functions. In the case of pairs of LUT-FF were used 6, which represents 5% of the available resources, which are 117 in this case. And, finally, out of the blocks of input/output (IOBs) were used 53 of 100 available, which represents a 53% usage. These data indicate that in order to synthesize the hardware there are very few resources.

5.2 Definition of the set of test signals

For the testing of the hardware design of the center CD, in the first place, they extracted a representative sample of the set of signals obtained during the stages of modeling. This subset consists of values for each of the signals that are involved in the implementation of the center CD, these are: ${}^{D}A_{CD}$, ${}^{M}I_{CD}$ and ${}^{R}I_{CD}$. These values were extracted from the testing and validation of the theoretical model, and were obtained from clinical trials during the stage of modeling [Soriano, 01]. These values, of origin continued by the analog nature of the biological system, were discrete for your use in the digital prototype hardware, which was done by the value obtained from the result of multiplying each value by the scale 10^3:

$$Value_{Fixed\text{-}Point} = integerPart\ (Value_{Floating\text{-}Point} * 10^3) \quad (10)$$

For simplicity, in the following graphic shows the evolution of the values of the signals, which also reflects the urodynamic system. Figure 11(a) shows the evolution of the signal ${}^{D}A_{CD}$, figure 11(b) the evolution of the signal ${}^{M}I_{CD}$ and finally the figure 11(c) shows the signal values ${}^{R}I_{CD}$.

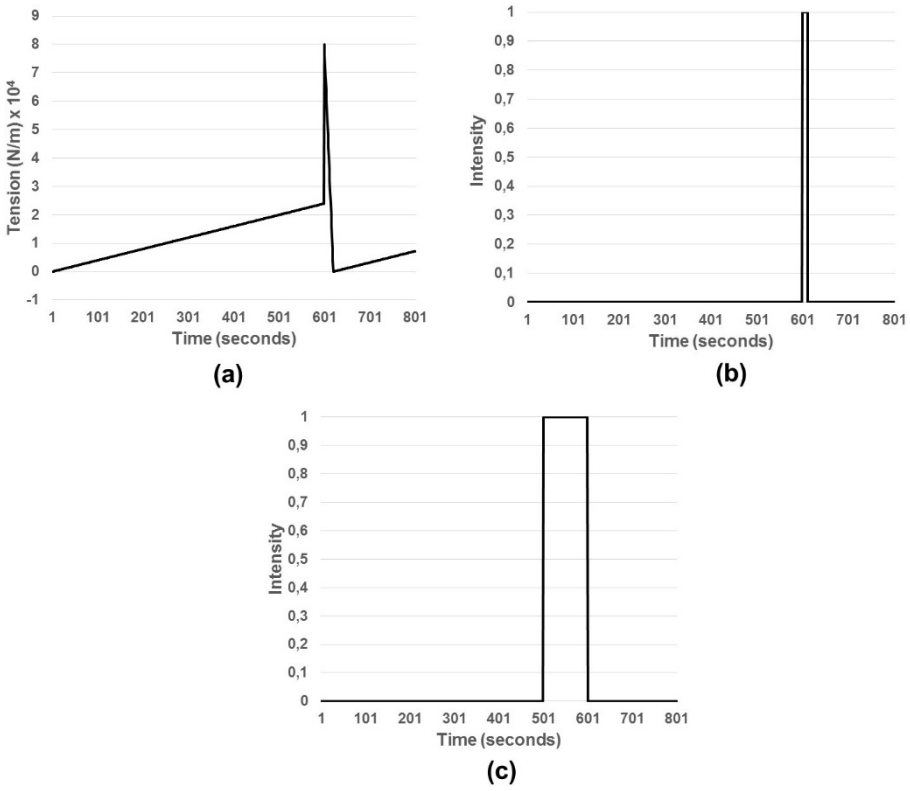

Figure 11: a) Afferent Signal ${}^{D}A_{CD}$, b) Internal Signal ${}^{M}I_{CD}$, c) Internal Signal ${}^{R}I_{CD}$

The signal ${}^{D}A_{CD}$, figure 11(a), shows how the pressure of the detrusor muscle grows up to a point at which has a sudden increase to then go decreasing quickly. The signal ${}^{M}I_{CD}$, figure 11(b), begins in a state of inactivity until the moment that is active for a short time to return to the initial state of inactivity. Finally, the chart signal ${}^{R}I_{CD}$, figure 11(c), indicates that this signal is inactive several seconds until it is needed that is active, this happens for a relatively short interval of time to go back to the idle state. This dynamic describes how the bladder detrusor pressure will increase as a person is feeling desire of micturition, until it reaches a point at which it is necessary to

produce the signal of voluntary retention, and reached the maximum pressure, i.e. that the person feels many desire to urinate, produces the signal of voluntary micturition.

In addition to the subset of input signals, were also defined the values associated with thresholds ${}^{D}H_{CD1}$ and ${}^{D}H_{CD2}$. These values, although are particular to each person, could be set to produce a behavior of the LUT normal for a human being without dysfunctions, in particular the values are 2.00 and 18.2 respectively.

And finally also determined the set of values that should be obtained as a result in the output signals ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$, whose evolution is shown in figure 12 (a) and (b). These values were also discrete using the same method of input signals.

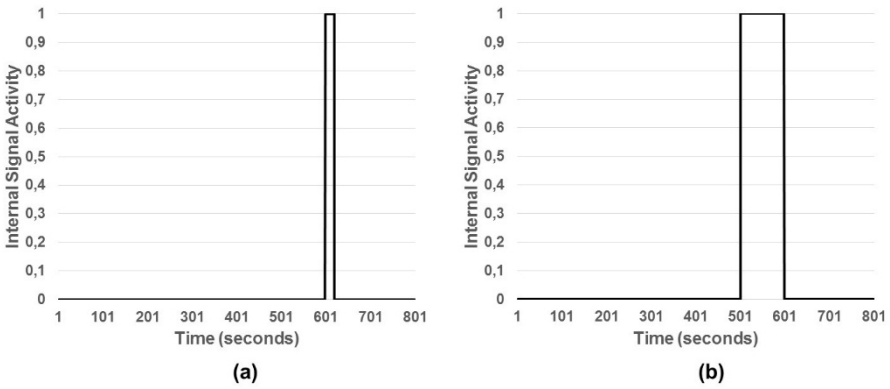

Figure 12: a) Internal Signal ${}^{CD}I_{PA}$, b) Internal Signal ${}^{CD}I_{PS}$

5.3 Isolated hardware test

The first test was to make the circuit synthesized in the FPGA to the sequence of input signals described above and pick up the signals that the system provides as a result, the signals ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$.

Figure 13 shows the execution exhibited by the hardware, not shown throughout the period of implementation but in particular the time span in which occurs the pressure spike in the detrusor muscle and, therefore, the generation of signals to cause both voluntary retention as the subsequent micturition, which may be observed: all input signals, exit, thresholds and their behavior in the time since it has captured its state at every moment and the value of all the signals to study its evolution.

In figure 13 have been identified 6 states or times when important events occur. Appreciated as in the state 1 the internal signal ${}^{CD}I_{PA}$ output that is the signal that it sends the center CD toward the center of the preoptic area (PA), maintains its value at 0 since that the person is in the phase of storage, up to that at the instant of time is marked with 2 signal takes value 1, or is activated due to the individual starts the phase of micturition, until the moment marked with 3 returns to be disabled, because it has completed the phase of micturition and begins the process again of storage of urine.

It can also be seen as in the instant of time marked with 4 internal signal ${}^{CD}I_{PS}$ output that is the signal that it sends the center CD toward the center pontine storage (PS), maintains its value in 0 due to the fact that the person is in the phase of storage, up to that at the instant of time is marked with 5 signal is enabled as the person begins to feel the urge for micturition but the atmosphere that surrounds it is not the most appropriate to initiate micturition; at the moment marked with 6 signal is turned off again, at this time the person is in a suitable environment to begin the phase of micturition therefore this signal is switched off and starts the micturition.

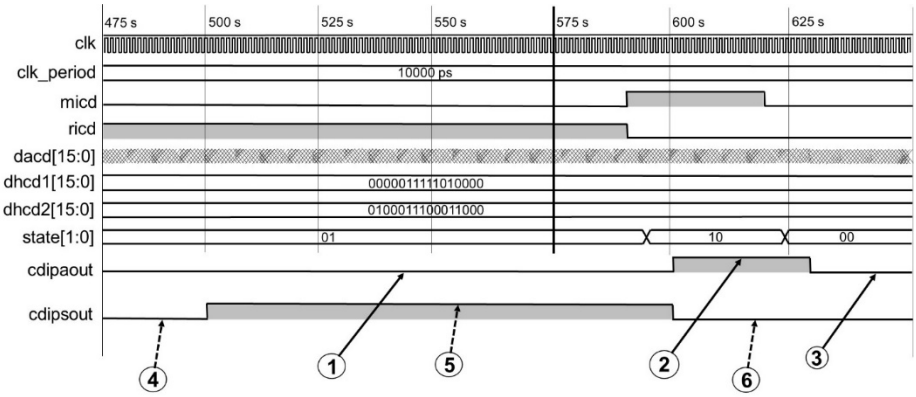

Figure 13: Values of the signals ${}^{CD}I_{PA}$ y ${}^{CD}I_{PS}$

After studying the results we can conclude that the synthesized hardware reproduces the behavior of the center CD, at least when it is used in isolation, since the signals resulting from the execution obtained are consistent with the expected values and shown in figure 12 (a) and (b).

5.4 Tests of the built-in hardware to the simulator of the LUT

As part of the testing process it was decided to incorporate the hardware prototype of the CD to the simulator center system neuroregulatory lower urinary tract that was already built in previous work [Soriano, 01] [García et al., 02a]. This simulator was built during the work of modeling of the LUT with the intention of being able to observe and evaluate independently the behavior of each of the centers that are modeled and the LUT, along with the signal sets of evidence obtained clinically, for well check that both the general model as your instance in the concretization of the LUT met with the behavior of the system neuroregulatory real human.

The application has two functional blocks. A first block, figure 14, where the simulation is performed by system, charging the set of input signals, regulating the thresholds of the centers and launching the execution. This execution can be step by step or execute by complete with all the sample values, being able to observe in each stage as they evolve the values of each of the centers.

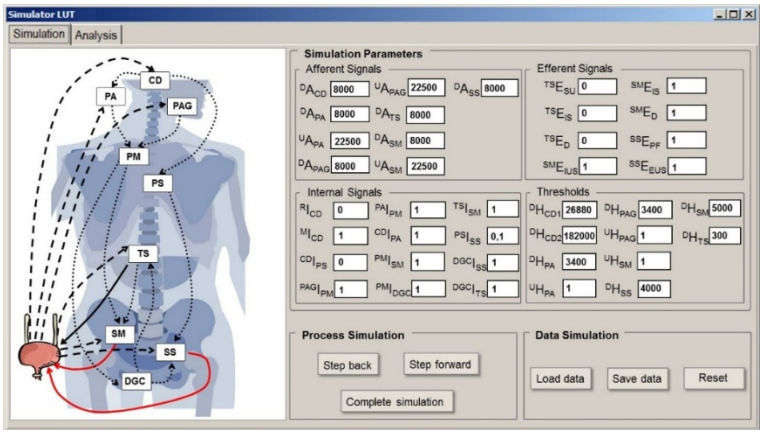

Figure 14: Neuroregulatory system simulator of LUT

The second part, figure 15, allows us to analyze the detailed evolution of each of the signals that pass through the system, which allows you to validate if your evolution is correct, that occurs when there is dysfunction or the exact moment in which the system is not behaving as expected.

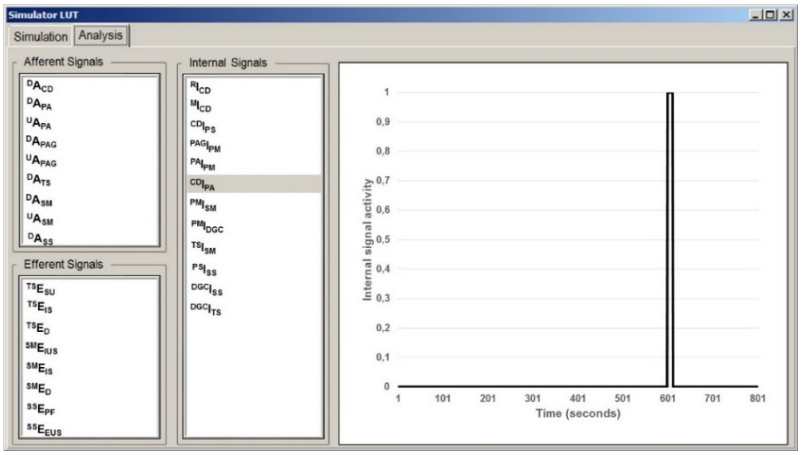

Figure 15: Neuroregulatory system simulator of LUT, signal analysis $^{CD}I_{PA}$

Using this simulator as a basis, it has been modified the software so that the center processing CD now moves to develop the FPGA. Now all the signals are sent to the hardware, which processes it according to the design specification and returns to the software the result of its processing. The connection of both systems is performed via USB interface, so that the software launches the implementation of the model, and at the time that a signal must be processed by the center CD, this is sent to the hardware

and wait for the result. Figure 16 shows the working environment as was used after incorporating the FPGA to the system software.

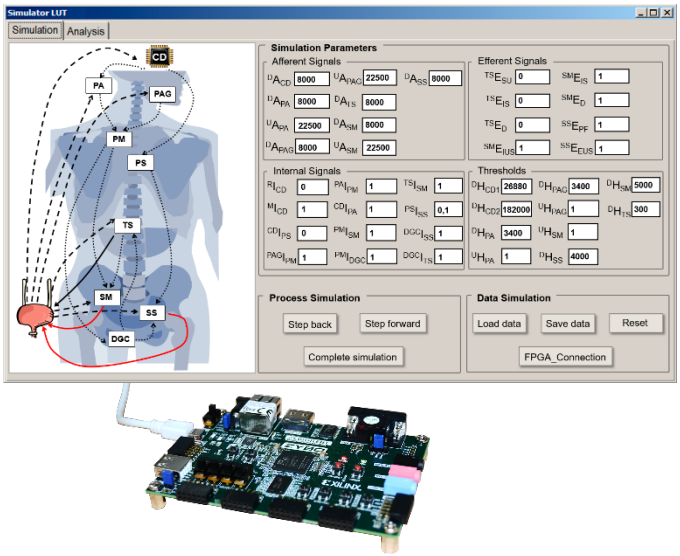

Figure 16: Work environment

When operating the simulator, but this time with the center CD running on the FPGA hardware, we were able to verify that the expected behavior of the complete system is once again lies with the obtained during the previous tests with all the modules executed via software. In Figure 17 shows the evolution of signals ${}^{CD}I_{PA}$ and ${}^{CD}I_{PS}$, and again, it has been found that when the hardware is used in conjunction with the rest of the elements of the system, their behavior also corresponds with the expected and therefore with the behavior of the Cortical-Diencephalic biological center.

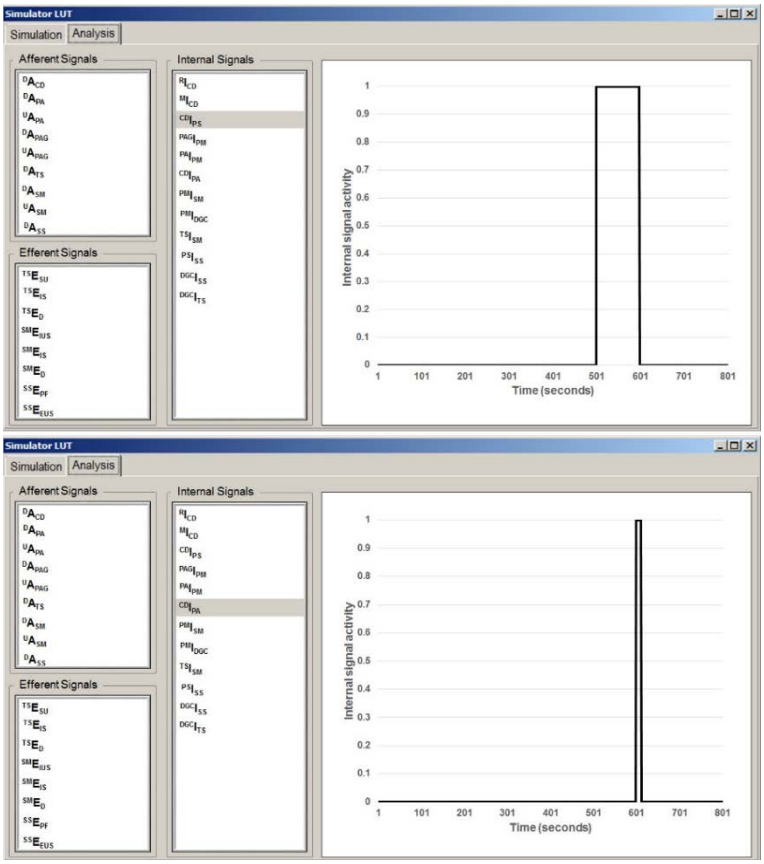

Figure 17: Result of the execution of the simulator with the FPGA integrated

At the same time, the dynamics of the rest of the system are also checked that are equivalent to the execution mode when all modules are executed on software, leaving thus demonstrating that the hardware generated is equivalent to the software and therefore exhibits the same behavior as the original model and that the biological system neuroregulatory.

6 Conclusions

In this paper we have identified the functioning and composition of a neuronal center form the neuroregulatory system in humans, the Cortical-Diencephalic center. In addition it has been proposed an original design and a hardware architecture that has been validated through the implementation of a prototype in FPGA and its incorporation into the simulator for the existing lower urinary tract. In the study can be seen as the behavior of the curves obtained from urodynamic tests and simulations

from this description hardware are equivalent to the results achieved from the tests carried out with the existing theoretical model.

With this paper sets the foundation of the hardware design of the rest of the neuronal centers that make up the neuroregulatory system in human beings. It has been proved as after the hardware synthesis of the design on the FPGA, the necessary resources are scarce, making it possible the final development of a neuroregulatory system based on SoC from the performance of a large number of nerve centers to carry out complex functions.

The prototype allows you to correct the dysfunctions in neuroregulatory system associated with a single neuronal center, in particular the Cortical-Diencephalic center. Up to now, this was not feasible. Much as there are solutions that involve replacing virtually the entire neuroregulatory system, including the centers that are operating correctly.

As future work, in the short term, we will continue the analysis and validation of this hardware design with other neural centers which will permit us to consider the needs and requirements of each hardware of the regulatory centers in order to generalize to the maximum the proposal. This will lead us, in the medium term, to be able to design a chip that can integrate multiple neural centers working together with the objective to manage a neuroregulatory system. In the longer term, we will obtain the creation of a chip of neural centers fully parameterized and programmable that can monitor systems, both biological and artificial requiring or conform to this type of control self-regulated, also achieving the construction of systems to help medical professionals in the decision-making and the detection of dysfunctions.

References

[Bortolini et al., 14] Bortolini, M. A. T., Bilhar, A. P. M., a Castro, R.: Neural control of lower urinary tract and targets for pharmacological therapy., International urogynecology journal, vol. 25, no. 11, pp. 1453–62, Nov. 2014.

[Chicca et al., 14] Chicca, E., Stefanini, F., Bartolozzi, C., Indiveri, G.: Neuromorphic Electronic Circuits for Building Autonomous Cognitive Systems, Proceedings of the IEEE, vol. 102, no. 9, pp. 1367–1388, Sep. 2014.

[Corradi et al., 14] Corradi, F., Zambrano, D., Raglianti, M., Passetti, G., Laschi, C., Indiveri, G.: Towards a Neuromorphic Vestibular System, Biomedical Circuits and Systems, IEEE Transactions on, vol. 8, no. 5, pp. 669–680, Oct. 2014.

[Dinu et al., 10] Dinu, A., Cirstea, M.N., Cirstea, S.E.: Direct Neural-Network Hardware-Implementation Algorithm. Industrial Electronics, IEEE Transactions on, vol. 57, no. 5, pp. 1845-1848, 2010.

[Ferber, 99] Ferber, J.: Multi-Agent Systems. An Introduction to Distributed Artificial Intelligence. Addison-Wesley, 1999.

[Fernández and Payá, 05] Fernández, R., Payá, S.: Robust Modelling of Biological Neuroregulators, Engineering in Medicine and Biology 27th Annual Conference, no. 5, pp. 2981–2984, 2005.

[Fiack et al., 15] Fiack, L., Rodriguez, L., Miramond, B.: Hardware design of a neural processing unit for bio-inspired computing. New Circuits and Systems Conference (NEWCAS), 2015 IEEE 13th International, pp. 1-4. June, 2015.

[Flaherty et al., 10] Flaherty, J. C., Guillory, K. S., Serruya, M. D., Caplan, A. H.: Transcutaneous implant. Google Patents, 2010.

[Fowler et al., 08] Fowler, C.J., Griffiths, D., de Groat, W.C.: The neural control of micturition, Nature Reviews Neuroscience 9(6) 453-466, june 2008.

[García et al., 02] García, J.M., Macía, F., Soriano, A., Flórez, F.: A Multi-Agent System uses Artificial Neural Networks to Model the Biological Regulation for the Lower Urinary Tract, WSES Conference on Neural Networks and Applications. Interlaken (Switzerland). (2002), 162-167.

[García et al., 02a] García, J.M., Romero, J., Macia, F., Soriano, A.: Modeling and simulation of neuronal regulator of the lower urinary tract. Urodynamics Applied, 15 (2) 2002.

[García et al., 02b] García, J.M., Soriano, A., Maciá, F., Ruiz, D.: Modelling of the sacral micturition centre using a deliberative intelligent agent, Proceedings of the IV International Workshop on Biosignal Interpretation (BSI 2002). Como (Italy). (2002), 451-454.

[García et al., 03] García, JM., Maciá, P. F., Soriano, P. A., Ruiz, F. D.: Simulation of the Neuronal Regulador of the Coger Urinary Tract Using a Multiagent System. Lecture Notes in Computer Science. Springer-Verlag, 2687 (2003), 591-598.

[Gil et al., 07] Gil, D., Soriano, A., Montejo, C. A.: Embedded System For Diagnosing Dysfunctions In The Lower Urinary Tract. Proceedings of the 2007 ACM symposium on Applied computing pp. 1695–1699, 2007.

[Gil et al., 11] Gil, D., Johnsson, M., García, JM., Payá, A. S., Fernández, D. R.: Modelling of urological dysfunctions with neurological etiology by means of their centres involved, Applied Soft Computing, vol. 11, no. 8, pp. 4448–4457, Dec. 2011.

[Girau and Torres-Huitzil, 07] Girau, B., Torres-Huitzil, C.: Massively distributed digital implementation of an integrate-and-fire LEGION network for visual scene segmentation, Neurocomputing, Volume 70, Issues 7-9, March 2007, Pages 1186-1197.

[Groat, 06] de Groat, W.C.: Integrative control of the lower urinary tract: preclinical perspective, British. Journal of Pharmacology 147 (2s) (2006) S25–S40

[Indiveri and Horiuchi, 11] Indiveri, G., Horiuchi, T. K.: Frontiers in Neuromorphic Engineering. Front Neurosci. 5:11810.3389/fnins.2011.00118 (2011).

[Jan et al., 06] Jan L. S., Ignace Th.C. H., Alexander H. W.: Localization and motion perception during smooth pursuit eye movements. Biomedical and Life Sciences, Springer Berlin / Heidelberg. Volume 171, Number 4, pp 448-458, June 2006.

[Ji et al., 15] Ji, Y., Ran, F., Ma, C., Lilja, D. J.: A hardware implementation of a radial basis function neural network using stochastic logic. In Proceedings of the 2015 Design, Automation & Test in Europe Conference & Exhibition . EDA Consortium, San Jose, CA, USA, 880-883. 2015.

[Junjie, 05] Junjie, X.: Desing and hardware co-simulation of a digital cochlear implant, Thesis (2005).

[Kawasetsu et al., 14] Kawasetsu, T., Ishida, R., Sanada, T., Okuno, H.: A hardware system for emulating the early vision utilizing a silicon retina and SpiNNaker chips, in Biomedical Circuits and Systems Conference (BioCAS), 2014 IEEE, 2014, pp. 552–555.

[Kinder et al., 99] Kinder, M.V., Bastiaanssen, E.H.C., Janknegt, R.A., Marani, E.: The Neuronal Control of the Lower Urinary Tract: A Model of Architecture and Control Mechanisms, Archives of Physiology and Biochemistry, 107 (1999) 203-222.

[Leong and Jin, 03] Leong, M. P., Jin, C. T.: An FPGA-Based Electronic Cochlea, Journal on Applied Signal Processing 2003:7, pp. 629–638.

[Martínez et al., 02] Martínez, A., Romero, S., Ros, E., Prieto, A., Pelayo, FJ.: Reconfigurable hardware implementation of a model of retina. Proceedings of the Second Conference on Field Programmable Logic and Applications (JCRA'2002), 97-101.

[Martínez et al., 05] Martínez, A., Pelayo, F.J., Morillas, C., Romero, S., Pino, B.: Automatic Generation of Bio-inspired Retina-Like Processing Hardware. Computational Intelligence and Bioinspired Systems Lecture Notes in Computer Science Volume 3512, 2005, pp 527-533.

[Mead, 90] Mead, C.: Neuromorphic Electronic Systems, Proceedings of the IEEE, 78 (10), Oct. 1990.

[Méndez, 08] Méndez, D.G.: Modeling and simulation of neurobehavioral lower urinary tract. System diagnostic support, Doctoral Thesis. Department of Computer Technology, University of Alicante, in September 2008.

[Meng, 06] Meng, Y.: A Mobile Vision System with Reconfigurable Intelligent Agents. Neural Networks, 2006. IJCNN '06. International Joint Conference on. pp. 1483-1488, 2006.

[Meza-Escobar et al., 08] Meza-Escobar, JH., Vera-Lizcano, M., Velasco-Medina, J.: Cochlear Models Hardware Implementation using FPGAs. 2008.

[Moffitt et al., 10] Moffitt, M. A., Carbunaru, R., Whitehurst, T. K., Mann, A. E.: Electrode contact configurations for an implantable stimulator. Google Patents, 2010.

[Moore et al., 12] Moore, S. W., Fox, P. J., Marsh, S. J. T., Markettos, A. T., Mujumdar, A.: Bluehive - A field-programable custom computing machine for extreme-scale real-time neural network simulation, in Field-Programmable Custom Computing Machines (FCCM), 2012 IEEE 20th Annual International Symposium on, 2012, pp. 133–140.

[Morrison et al., 05] Morrison, J., Birder, L., Craggs, M., de Groat, W.C., Downie, J., Drake, M., Fowler, C.J., Thor, K.: Neural control, Incontinence 1 (2005) 363-422.

[Mota, 08] Mota, F. S.: Bio-inspired circuits for realtime motion evaluation. Tesis doctoral. Dipartamento Di Ingegneria Elettrica Ed Elettronica, Università Degli Studi Di Cagliari, 2008.

[Osio et al., 06] Osio, J., Salguero, F., Rapallini, J., Quijano, A.: Analysis of Computational Models for Embedded Systems. XII IBERCHIP, IWS06. Costa Rica, 2006.

[Payá et al., 13] Payá, A. S., Fernández, D. R., Gil, D., García Chamizo, J. M., Pérez, F. M.: Mathematical modelling of the lower urinary tract. Computer methods and programs in biomedicine, vol. 109, no. 3, pp. 323–338, Mar. 2013.

[Rodriguez et al., 13] Rodriguez, L., Fiack, L., Miramond, B.: A neural model for hardware plasticity in artificial vision systems. Design and Architectures for Signal and Image Processing (DASIP), 2013 Conference on, pp. 30-37. October 2013.

[Romero et al., 05] Romero, S., Pelayo, F. J., Morillas, C. A., Martínez, A., Fernandez, E.: Reconfigurable Retina-like Preprocessing platform for cortical visual neuroprostheses, volume 3, chapter Neural Engineering: Neuro-Nanotechnology - Biorobotics, Artificial Implants and Neural Prosthesis. IEEE Press Series on Biomedical Engineering, metin akay edition, 2005. ISBN: 0-471-68023-0.

[Ruiz et al., 04] Ruiz, F. D., García, JM., Maciá P. F., Payá S. A.: Modeling the Distributed Control of the Lower Urinary Tract Using a Multiagent System, Lecture Notes in Artificial Intelligence, Springer-Verlag 3131 (2004) 104 -114.

[Ruiz et al., 05] Ruiz, F. D., Garcia, JM., Macia, F.: Modelling of Dysfunctions in the Neuronal Control of the Lower Urinary Tract, pp. 203–212, 2005.

[Ruiz, 03] Ruiz, F. D.: Modeling of self-regulation of biological systems. Characterization and correction of neurogen urinary dysfunctions in human, Ph.D. dissertation, University of Alicante, Alicante, Spain, 2003.

[Samie et al., 13] Samie, M., Dragffy, G., Tyrrell, A. M., Pipe, T., Bremner, P.: Novel Bio-Inspired Approach for Fault-Tolerant VLSI Systems. IEEE Transactions on very large scale integration (vlsi) systems, vol. 21, no. 10, October 2013.

[Soriano, 01] Soriano, A.: Modeling and Simulation of the Neural Regulator of the Lower Urinary Tract, PhD Thesis, Ph.D. Dissertation, Dept. Comp., University of Alicante, Alicante, Spain, 2001.

[Tsompanas and Sirakoulis, 12] Tsompanas, MA., Sirakoulis, GCh.: Modeling and hardware implementation of an amoeba-like cellular automaton. Bioinspiration & Biomimetics, doi: 10.1088/1748-3182/7/3/036013, May 2012.

[Yucel and Baskin, 04] Yucel, S., Baskin, L.S.: An anatomical description of the male and female urethral sphincter complex, The Journal of Urology 171 (5) (2004) 1890–1897.

[Zicari, 13] Zicari, P.: Efficient and high performance FPGA-based rectification architecture for stereo vision. Microprocessors and Microsystems. Vol 37, issue 8, pp 1144-1154, November 2013.