A modular configurable system for closed-loop bidirectional brain-machine interfaces

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Abstract— **Extending bidirectional Brain-Machine Interfaces tailored for specific experiments with additional software and hardware tools can be very onerous, if not impossible. To overcome this problem, we developed a modular configurable system by modifying the architecture of an existing bidirectional BMI. This modular system enables the seamless and efficient inclusion of new features and the integration of new protocols without changing the native system's overall structure. By introducing a platform for the implementation of BMI algorithms on neuromorphic chips, this method represents a step towards the development of low-power, compact and computationally powerful tools for clinical applications.**

I. INTRODUCTION

During the late nineties the technological progress for the interconnection of living neural tissue with artificial devices was one of the main factors that led to a rapid growth of the research field known as brain-machine interfaces (BMIs) [1]. After almost twenty years, the unquestionable scientific results achieved in this frontier research also highlighted the hurdles in the technological transfer of such results into clinical applications [2]. This is also due to the fact that BMI systems comprise several dedicated modules, each tackling specific research and technological challenges. The coupling of the electrodes with the neural tissue, the computational capabilities of the processing unit, the performances of the decoding algorithms and the generation of motor commands to control external devices represent the main topics of different research fields. The algorithmic, software and hardware heterogeneity of the modules assembled together by the researchers in developing BMI systems makes it difficult to exchange knowledge or include additional modules developed by different laboratories and, at the same time, to compare the performances of these systems. In this paper, we present a new modular and configurable implementation of a closed loop bidirectional BMI system, previously developed and tested with anesthetized animals [3], [4]. The modular configuration of this system creates a flexible structure in which new or updated versions of individual modules even based on different communication protocols can be inserted or replaced without having to change the whole system.

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II. A MODULAR BIDIRECTIONAL BMI

The architecture of a bidirectional BMI usually comprises five main components: an *Acquisition System* (AS) to record the neural signals, a *Decoder* (DE) to decode the neural activity that need to be translated into motor commands, an external *Dynamical System* (DS), an *Encoder* (EN) and Stimulation System (SS) with the goal of encoding the information collected from the environment and of translating it into stimuli to be delivered directly into the brain [5].

In this paper we consider a BMI that uses two microwire electrode arrays inserted into different regions of the cortex as described in [6]. The AS records, amplifies and performs an A/D conversion of the neural signal acquired from the intracortical array placed in the motor cortex. The AS might also perform further signal processing, such as spike detection and sorting, local field potential computation, etc. Spike occurrences and other information are then sent to the DE that interprets them, transforming the neural data into proper commands to drive the movement of the DS. The DS evolves for a certain time interval and its corresponding final state is converted by the EN into an appropriate electrical stimulation pattern. The SS delivers these stimuli directly to the rat's sensory cortex by using a second microwire electrode array with the goal of giving information about the actual status of the DS. The stimulation pattern is usually composed by a bi-phasic current pulse train of given amplitude and duration applied to a subset of intracortical micro-electrodes. Despite the main components being similar throughout all of the existing closed-loop BMIs proposed so far, each of them depends on specific and mutually dependent hardware, software and communication modules, with low compatibility and, hence, flexibility. This is one of the main reasons why each lab usually built form scratch its own BMI and the technology sharing rate is really low.

We propose a flexible, modular implementation based on a core, the *Managing Unit* (MU) that serves as coordinator of the information flow across a series of modular satellites that complete/enhance the BMI itself as shown in figure 1.

Thanks to the MU, each satellite can be independently instantiated on different platforms and, for example, during the development and prototyping phases, they can be explored and tested on software running on general purpose CPUs. At a later stage they can be progressively moved to more specialized hardware platforms, up to the implementation of dedicated modules such as the neuromorphic chips. In the

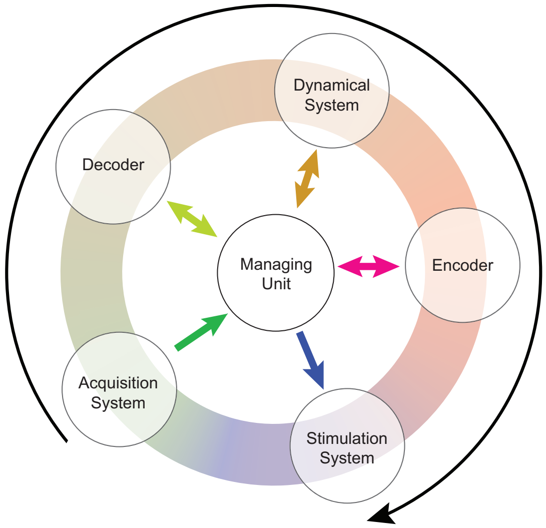

Fig. 1. General Scheme of the modular configurable system for bidirectional BMIs. On the rainbow donut are depicted a series of different satellites that communicates, in mono or bi directional way, with the central MU which manages their data flow. In particular the AS catches the neural signal that is collected from MU, which sends the rehashed data to the DE. It returns to the MU the result of the decoding policy that is translated into a command that drives the DS. When necessary the MU can retrieve the current state of the DS and through the EN it can decide for the most appropriate stimulation that SS will deliver to the brain.

prototyping phase the system trades off flexibility for power consumption and compactness that are instead optimized with the use of dedicated HW devices. Using this approach we started the development of the MU and step-by-step we gradually added each module to complete the closed loop interface. In the following we present the target closed-loop BMI system, describing in detail each component and the interfacing to the MU.

Figure 2 shows a possible implementation of the described system architecture. This system is composed by a ZedBoard hosting both the Managing Unit and the Encoder, a RZ2 BioAmp Processor (Tucker-Davis Technology, TDT, Gainesville, FL) as Acquisition System, a RX7 Stimulator Base Station (TDT) as Stimulation System, the Reconfigurable On-Line Learning neuromorphic processor chip as Decoder and a planar two degrees of freedom robotic device as Dynamical System.

A. Managing and Encoder Units

The Managing Unit represents the core of our system and we choose a development board named *ZedBoard* based on a Xilinx Zynq©-7000 which is composed by a fully programmable logic (FPGA) and a Dual ARM© Cortex™A9 MPCore™(667MHz). It has a 512 MB DDR3 memory and a 16GB SD card flash storage unit. Its huge connectivity (Ethernet, UART, several I/O ports and many others) and the possibility to have a microprocessor (μP) and a programmable logic on the same device makes the ZedBoard a perfect candidate to be the main core (MU) of a bidirectional BMI. The ZedBoard can be logically subdivided in two main parts: a microprocessor (μP) with a memory block (MM) and a Programmable Logic Module (FPGA). A lighter and faster version of the commercial operating system Linux Ubuntu runs on the MM providing a series of C/C++ and Python built-in libraries and compilers for software development. We used it to host the core of the managing unit constituted by a series of algorithms to regulate the flow of information across all of the satellites and the FPGA and that we called *BMI Algorithm*.

Being the MM a general purpose hardware, we also added some software modules of the brain-machine interface such as the Dynamical System Controller, the Encoder (EN) and the Simulation Unit.

a) The *Dynamical System Controller* translates the desired state of the dynamical system into a proper command through the Dynamical System Interface that handles the communication to the specific robotic system.

b) The *Encoder* retrieves the final state of the DS and, through a look-up table, selects the most appropriate stimulation pattern that has to be delivered by the SS. In this first implementation we built the encoder in a way that there is a correspondence between each position of the controlled device with a stimulation pattern as described in [3].

c) The *Simulation Unit* is composed by a series of Python and C/C++ functions for the simulation of the DE and DS modules; this modularity allows for flexible prototyping and algorithm development before porting the closed loop BMI to hardware.

At this stage we implemented also a software version of the decoder module based on python scripts that simulates a spiking neural networks for learning and classification, specifically designed to be hardware compliant. This feature is crucial because it allows us to test the behavior of the neuromorphic chip in a closed-loop system via a software simulation before connecting the hardware.

The same happens for the DS module because the MM can simulate a full dynamical system even in absence of the external robotic actuator, by directly calculating the temporal evolution of the dynamical system after the application of the decoded input.

Finally, the MM is also able to import/export data from the ZedBoard Ethernet port using the UDP protocol. This allows the user to run the entire closed loop process off line by importing a sufficiently large and representative neural data and by disconnecting the AS and SS.

The other fundamental block of the ZedBoard is the Programmable Logic Module programmed by the MM and composed by the NeuElab and the Dynamical System Interface modules.

The NeuElab module acquires the rehashed brain signals from the BMI Algorithm and routes them, in the proper way, to the DE and vice versa. This means that the spikes are encoded with the AER protocol and sent to the Neuromorphic chip (DE), conversely, the chip output AER spikes are acquired and the resulting decoded response is sent to the Dynamical System Interface. NeuElab

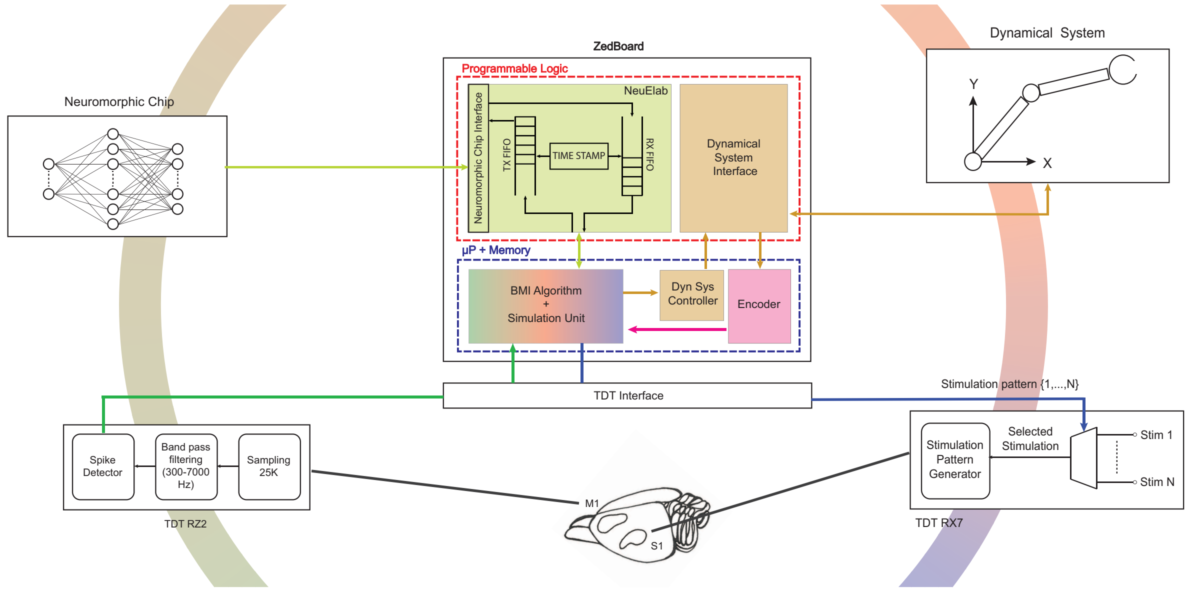

Fig. 2. Real configuration of the modular bidirectional BMI. Here the MU is represented by a ZedBoard development board that communicates via UDP protocol with a TDT RZ2 BioAmp (AS) and a TDT RX7 Stimulator (SS). On the other side the ZedBoard is connected to the ROLLS neuromorphic processor (DE) that implements a perceptron neural network that, properly trained, is able to decode the neural signal coming from rat motor cortex. The result of the decoding stage is translated by the MU into a two-dimensional force which is converted into digital signals able to drive the motors installed on the 2 degrees of freedom robotic device. This latter communicates back to the software Encoder, implemented on the ZedBoard, its final state which is transformed into a stimulation pattern that is subsequently delivered by the TDT RX7 into the somatosensory cortex of the subject.

is composed principally by two different FIFOs that drive the data flow from/to the Reconfigurable On-Line Learning neuromorphic processor chip, the RX and TX Fifo.

a) The *RX Fifo* is filled with the spike activity of the neurons of the ROLLS chip. Each spike contains two values, the address of the neurons that generated it and the time stamp associated by the TimeStamp block. In this way each spike has its unambiguous identification and time stamp associated to it. The received couples of address and relative time stamp are then sent to the BMI algorithm to be translated into a force b) The *TX Fifo* is filled with the address of the neuron to which the spike will be sent and the time relative to the other spikes, by associating a delay time value in units of TimeStamp block. It will be then read by the NeuElab that will send each spike to the correct neuron at the correct time.

The second block, the Dynamical System Interface modules, acquires from the Dynamical System Controller the commands to be translated into digital signals to drive the external device. If the DS is able to return feedback about its current state the Dynamical System Interface has to collect and redirect it to the Encoder Unit. In the case in which the DS is driven in an open-loop fashion the current state will be communicated to the EN directly from the BMI Algorithm itself.

B. Acquisition and Stimulation Units

The TDT RZ2 BioAmp Processor uses 8 Digital Signal Processors (400 MHz, 2.4 GFLOPS, 64MB SDRAM) to band filter (300-7000 Hz) the neural signal and to perform an on-line spike detection based on the standard deviation of the signal RMS. The spike occurrences can be sent to the MU by using two different modalities: a) a direct UDP connection between the ZedBoard and the RZ2 b) a TDT interface composed by a Windows PC equipped with a PCI Express TDT Optibit Interface PO5e that receives via optic fiber the data coming from the RZ2 and routes it via UDP to the ZedBoard.

The TDT RX7 Stimulator Base Station (5DSP, 100 MHz, 600 GFLOPS, 128MB SDRAM) can store in his memory several stimulation patterns and it is possible to associate for each of them a different stimulating electrodes. The above mentioned TDT interface allows to setup the stimulating patterns parameters as duration, frequency and amplitude of the biphasic stimulation pulse train. During the closed-loop BMI functioning, the stimulation code sent by the MU is able to recall one of the stored stimulation patterns that is subsequently D/A converted into a biphasic current stimulus and directly delivered to the stimulating intracortical electrodes. The TDT interface permits to run built-in tools in ordet to supervise and manage the RZ2 and RX7 functioning.

C. Decoder Unit

Neuromorphic chips are dedicated hardware devices that can reproduce some of the key properties of neural computation such as event-driven, cooperative, context-dependent processing, learning, and adaptation [7]. They are best suited for low-power applications where noisy and uncontrolled signals need to be decoded in real-time, for example to control external devices. In the proposed architecture, a multi-neuron neuromorphic chip, the Recurrent On-Line Learning Spiking (ROLLS) neuromorphic processor [8], is deployed for decoding the neural signals recorded from the rat?s brain

(DE) and producing the signals that will drive the robotic actuator (DS). The ROLLS processor is a full-custom mixed signal VLSI chip that uses low-power sub-threshold analog circuits to implement spiking neurons and biophysically realistic synapse dynamics, and asynchronous digital circuits to communicate the neurons action potentials via fast digital pulses. The ROLLS architecture comprises 256 adaptive exponential Integrate and Fire neurons [9] each receiving input currents from 520 synapses Out of all the synapses afferent to a neuron, 8 have digital programmable weights, 256 implement short term plasticity V and 256 spike-based learning circuits based on the model proposed in [10]. All synapses and neurons comprise additional digital circuits that can be used to configure both their individual properties (such as time constants, leak conductance, etc.) and the network internal connectivity. The on-chip programmable all-to-all connectivity allows the configuration of a wide range of neural networks topologies. The activity of the spiking neurons can be transmitted to off-chip devices in the form of prototypical address-events using the AER protocol [11]. In our setup we use the ZYNQ programmable logic to manage the flow of spikes from and to external devices. In the proposed closed-loop BMI, the ROLLS neuromorphic processor is used for the classification and decoding of spike patterns recorded from the rat's motor cortex, either online from the TDT recording unit, or offline, loading stored data sets from the MU, for tuning and characterization of the decoding algorithm.

III. CONCLUSION

The way in which the technology advances is a great opportunity for neuroscientists as it allows them to easily access the latest available technological tools and overcome existing bottlenecks and limitations [12]. In this scenario, it is crucial to develop systems that are flexible enough to easily include the latest technologies and tools in the part of the system already developed, without changing the entire architecture. An optimal solution is represented by modular architectures, in which each element can be developed and modified independently from the others and a central unit manages the exchange of information across each module. In this paper we presented an example of such a configurable architecture for developing closed-loop bidirectional brain-machine interfaces. We reconfigured existing BMI system into a new architecture that allows us to modify, substitute or add new features without having to restart from the beginning. The whole concept of the system has been developed *around* a central core that it is capable of managing the information flow across several modules that can be added to the main systems, managing also different protocols. In this way it is easy, for example, to simulate the behavior of the dynamical system, or of the decoding algorithm, before physically inserting them into the closed-loop. For the first time we showed a BMI closed-loop system capable of integrating modules based on the AER protocol and, hence, exploiting the emergent neuromorphic technology. The proposed system represents a powerful developmental platform for BMI research, specifically for testing the implementation of BMI algorithms on neuromorphic hardware. This approach has the potential of delivering compact, low-power and computationally powerful devices essential for transferring the BMI research to clinical products.

These features are essential for such clinical applications that need to use devices implanted in proximity of the brain under the skull that use wireless communication protocols to transfer the data outside the body [13].

Eventually, this approach will be useful for researchers that want to use updated technology and, more interesting, it represents a good solution which increases the possibility of exchanging knowledge between different laboratories working in the same field.

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