Received October 25, 2020, accepted November 9, 2020, date of publication November 23, 2020, date of current version December 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3040064

Implantable and Wearable Neuroengineering Education: A Review of Postgraduate Programmes

RAMI GHANNAM[1], (Senior Member, IEEE), GIULIA CURIA[2], GLAUBER BRANTE[3], (Senior Member, IEEE), SARA KHOSRAVI[1], (Student Member, IEEE), AND HUA FAN[4], (Member, IEEE)

[1]Engineering Education Research Group, James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, U.K.
[2]Department of Biomedical, Metabolic and Neural Sciences, University of Modena and Reggio Emilia, 41125 Modena, Italy
[3]Department of Electrical Engineering, Federal University of Technology - Paraná (UTFPR), Curitiba 80230-901, Brazil
[4]School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

Corresponding author: Rami Ghannam (rami.ghannam@glasgow.ac.uk)

This work was supported by UK's Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/R511705/1. It was also supported by CAPES, Finance Code 001, and CNPq.

ABSTRACT Neurological diseases (NDs) such as epilepsy, dementia, Alzheimer's and Parkinson's disease currently affect almost two thirds of Europe's population. Furthermore, enormous financial commitments are required to deal with these diseases. Therefore, there is growing concern that countries with transitional economies may struggle to handle this financial burden, which warrants the urgent development of new technologies for early disease identification and treatment. Consequently, the aim of our article is to survey the range of postgraduate programmes that strive to nurture neuroengineering graduates who will excel in designing and developing implantable and wearable technologies for ND applications. Based on the basic building blocks of these technologies, we have identified four key areas that programmes need to cover, which include Neuroscience, Integrated Circuits, Communications and Signal Processing as well as Electronic Devices. According to our systematic review, a total of fifteen institutes satisfied our search criteria and provided the necessary neuroengineering training. The majority of these programmes are located in Europe and North America, which means that cross border and interdisciplinary efforts are required to develop educational programmes in countries most vulnerable to these diseases. We also provide recommendations for how these programmes can be delivered using non-traditional teaching approaches to ensure that graduates develop the necessary soft skills required by the constantly shifting job market.

INDEX TERMS Neuroengineering, wearables, implantables, engineering education.

I. INTRODUCTION

The enormous financial commitment required to deal with neurological diseases (NDs) in Europe currently exceeds EUR 300 billion per year, with Parkinson's disease (PD) accounting for EUR 13.9 billion of that total [1]. In Europe, almost 60% of the population suffers from NDs and there are only 85,000 neurologists to provide care for around 900 million citizens across Europe [2]. In fact, it is the number three disease category causing disability in Europe.

In 2001, NDs such as dementia affected 60% of people living in developing countries, and this figure is expected to reach 71% by 2040 [3]. Moreover, the situation is more alarming in many developing countries, where several factors are leading to an increased risk of NDs [4], [5]. For example, the percentage of Egypt's population aged over 60 is expected to rise from 7% to 20.8% by 2050 [6]. This ageing population greatly increases the risk of developing NDs such as stroke, PD and Alzheimer's disease (AD). Moreover, the high proportion of consanguineous marriages in North Africa, West Asia and South India, which varies between 20% to 50% of all marriages in those regions [7], [8], has been attributed to an increased risk of developing NDs. Furthermore, the increased rates of urbanization, excessive caloric intake, unhealthy diet and lack of physical activity have all played a role in triggering neurological movement disorder [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Hadi Heidari.

PD is a neurodegenerative disease, whose global incidence rate is second only to AD [3]. According to [9], NDs are the second leading cause of death globally. Moreover, there has been an alarming rise in the number of deaths from NDs by 37% in the period between 1990 and 2015. In fact, the incidence rate of PD in people aged over 65 is 1%∼2%, and almost half of all PD patients in the world are located in China [4]. Thus, this global increase in the number of NDs during the past 25 years is a major cause for deaths and disabilities. Therefore, this will bring a heavy burden on families, societies and clinicians with expertise in neurological disorders. Policy makers and healthcare providers around the world should be aware of these trends to provide the necessary services to these communities [5], [9].

A. WEARABLE AND IMPLANTABLE TECHNOLOGIES

Wearable and implantable electronic devices can be used to improve the living conditions of patients suffering from NDs, such as PD [10]. Such devices aim to enable easy interaction between input hand gestures and a computer [11]. Common devices such as mice, keyboards, touchscreens, and game controllers are intuitive because they exploit the naturally sophisticated articulation of our hands. However, patients with NDs may not be able to interact effectively with these input devices. Therefore, a wide range of devices can be exploited for this purpose. The range of applications and locations of these wearable devices is shown in figure 1. These devices include head-mounted displays, wearable bracelet devices [12], contact lenses [13], gloves and many others.

FIGURE 1. Range of applications of wearable devices, as well as the location in which they can be used.

Implantable and wearable technologies have been used to monitor, track and record vital human signs. These devices typically consist of five main building blocks or modules, as shown in figure 2. These modules are the Interface, the Communications module, the Energy Supply and Conditioning module, the Data Processing module and the Integrated Circuits and Packaging module [14]. The "Interface" module is responsible for collecting information via sensors or other input devices, as well as presenting output information to the wearer. Similarly, the Communications module is responsible for transferring this information between the wearable and its wearer. The Energy Supply and Conditioning module is responsible for harvesting and managing the energy required to meet the needs of these components. The Data Processing module is responsible for processing, storing and managing the data collected from the Interfacing module. Finally, the Integrated Circuit and Packaging module is required to efficiently connect, encapsulate and manage these modules together.

Thanks to advancements in packaging and nanofabrication, it is now possible to embed these components into a small area and at a relatively low cost. Moreover, the emergence of the 5th generation (5G) wireless network will enable these Internet of Things (IoT) devices to be efficiently connected to ourselves and to experienced healthcare providers [15].

B. THEMATIC AREAS

Despite this recent progress, there are no specific postgraduate engineering programmes that train students in the field of implantable and wearable electronics for sensing and treating diagnosed NDs. Thus, engineers and scientists need to collaborate with physicians to understand patient requirements and to provide valuable feedback on the diagnostic approach as well as the overall design of these products.

In the literature, we have previously highlighted that undergraduate students will need to be trained in five thematic areas, which are Microelectronics (M), Artificial Intelligence (A), Neuroscience (N) and Integrated Circuits (IC) [16]. According to the building blocks shown in figure 2 and complementing our previous efforts regarding these five "MANIC" thematic areas required for training the next generation of "neuroengineering" undergraduates, we believe that postgraduates require training in four key themes or tracks, which are Neuroscience (N), Integrated Circuits (I), Communications and Signal Processing Systems (C) and Electronic Devices (E). Henceforth, these topics will be referred to as "NICE".

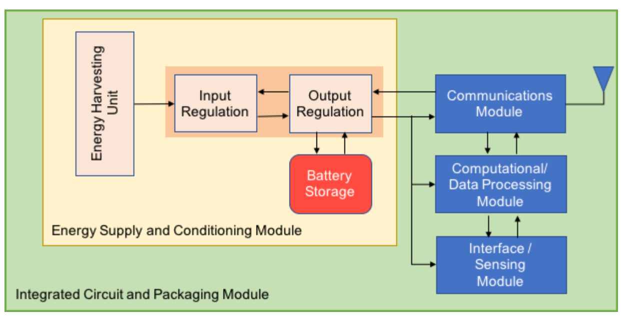

FIGURE 2. Building blocks of a wearable or implantable device.

We have taken this approach since the overlap between Integrated Circuits and Microelectronics does not need to be covered at the postgraduate level. Instead, we believe that a greater emphasis on Electronic Devices is necessary at the postgraduate level, where students should cover the basic components for switching, sensing, energy harvesting and power conditioning purposes. For the purpose of this review, we focus on the energy harvesting, conversion and storage for wearable and implantable products.

Thus, we believe that any postgraduate educational programme should contain elements of these four tracks in order to advance the progression of this technology, as suggested in figure 3.

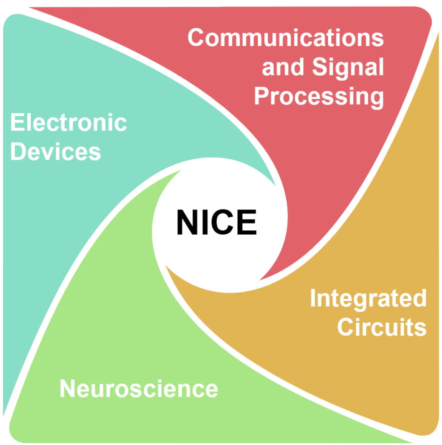

FIGURE 3. **Suggested components of the NICE programme.**

We will review the learning resources that have been developed in each of the four tracks mentioned above. Each of these tracks will play an integral role in the development of neuro-engineers specialized in implantable and wearable devices for NDs, and should be pursued concurrently, not in isolation. Before diving into the subject content, we shall first highlight some of the most recent advancements in wearable technologies for NDs in section 2. In section 3, we will subsequently discuss our methodology in systematically reviewing the postgraduate programmes that train engineers in neurological sciences. In section 4 we will present the results of our findings for each of the NICE subject areas. Moreover, we will discuss the results of our findings, as well as the possible methods that can be used to deliver such an innovative programme in section 5. Finally, concluding remarks are presented in section 6 of the article.

II. STATE OF THE ART

With the rapid development of microelectronics, integrated circuit technology and bio-medicine, wearable medical chips will have more functionality. Wearable technology is touted to play an important role in the research of nervous system diseases [1]. A physician's examination along with the Unified Parkinson's Disease Rating Scale (UPDRS) were mainly used for the clinical diagnosis of NDs such as PD [17]. However, the sensitivity of these methods is low and they are prone to ambiguities as well as subjective bias [17]. With the development of sensor technology and wireless communication technology, a growing number of wearable devices can now be used for the diagnosis of PD [18]–[20].

For example, the accelerated motion signals from three parts of the body of PD patients were collected by McBride *et al.* using a wearable sensor device with wired data transmission [21]. Moreover, Bobo *et al.* designed an acceleration signal recording device that can be worn on the wrist, which is a motion detection instrument based on computer vision and can automatically measure the tremor frequency [22]. Hofstoetter *et al.* also puts forward an acceleration signal recording system that can be worn on the fingertip to achieve the guidance of the optimization of deep brain stimulation parameters in patients with PD [23]. The study by Lee *et al.* [24] addressed the quantification of bradykinesia (slowness of movements) with the purpose of tracking PD's progression. Wearable devices are the effective tools to realize PD early detection, disease diagnosis and efficacy feedback.

Wearable devices developed for PD focus on the measurement and detection of the most overt deficits, the motor aspects of the disease. However, most PD patients display motor and non-motor endpoints that vary within and between days, and functional disabilities in daily functioning in some patients may only include nonmotor phenomena, such as fatigue, anxiety, and depression [25]. Relatively few studies have focused on detecting the fluctuations of these complex manifestations [26], [27]. Indeed, there is urgent need to develop systems to monitor nonmotor endpoints in the home setting and continuously for days to detect variability within and between days and improve the diagnosis of PD, maybe even at an early stage of the disease.

Wearable devices measuring heart rate variability can be used to classify post-traumatic stress disorders [28], subclinical depression [29], stress [30] and, in combination with accelerometer, to identify subjects with schizophrenia [31]. Wearable devices and sensors monitoring vital parameters and physical activity, and detecting falls could help avoiding emergency situations and be used in healthcare for the aging population [32], [33].

In addition to diagnostic tools, wearable devices can be helpful for caregivers and family members who can, for example, be alerted by a wristband to monitor physiological signals in epileptic people [34], or by a GPS watch to track position of the patient affected by dementia or AD [35], [36].

For a comprehensive review on digital sensors in the context of mental health and NDs, the reader is referred to the article by Reinertsen and Clifford [37]. In particular, the authors emphasize the lack of standardization of devices available on the market. In this regard, an educational programme focusing specifically on wearable and implantable devices can help reducing this gap.

By their turn, communications and signal processing techniques have an intrinsic relationship with wearable devices for medical applications. From the communications point of view, modern IoT applications combine a set of sensor devices, either wearable or implantable, collecting and transmitting data to a central gateway [38]. Subsequently, both the gateway and the devices may employ state-of-the-art signal processing techniques, such as machine learning and artificial intelligence. This powerful combination enables a broad distribution of individualized diagnostics and therapy applications in:

i The early identification of ND, *e.g.*, resorting to speech recognition or identification of the decrease in the control over fine motor skills;
ii Patient monitoring at home, by means of sensors or even the smartphone;
iii To help treatment, *e.g.*, assisting doctors to adjust medication through data collection, giving commands to future implantable devices, *etc.*

In fact, the use of signal processing tools for neuroscience is not new and has been extensively developed over the past decades. Nevertheless, early techniques rely mostly on invasive neural recordings [39]. More recently, some studies employ acoustic information extracted from spontaneous speech to detect dementia from preclinical stages of subjective memory loss, to more severe conditions like mild cognitive impairment and Alzheimer's dementia [40]. Some studies in this area combine natural language processing, looking for lexical/syntactic complexity and semantic coherence, with speech signal processing, analyzing prosody, pause and speech rates, as well as articulation [40]–[42].

In addition, vocal impairments have also been employed to detect initial stages of PD [43]. Common to these studies is that (deep) machine learning techniques become crucial assets to extract information from the vocal recordings. Some examples in [44], [45] literally bring these applications to the palm of our hands, combing wearable devices and deep learning techniques computationally efficient to run in smartphones, as a means of repeated monitoring and tracking of individuals during their daily living activities, which is of great importance for treating chronic diseases [45]. Let us remark that, although most artificial intelligence and machine learning techniques are usually employed at the gateway side, which is more computationally efficient, the rapid development of these techniques have enabled them to be used on wearables, resulting in more comprehensive and advanced functionalities [46].

For recent advances in electronic devices, we focus our attention on the energy storage, conversion and harvesting devices. To ensure that wearables and implantables can be used for continuous health monitoring, they need to be truly autonomous and self-powered. Currently, most energy solutions are dominated by lithium-ion battery technologies, which are not ideal for future wearable and implantable products. These solutions are often rigid, bulky and require constant replacement. Consequently, Mackanic *et al.* have now developed a soft and stretchable battery that relies on a special type of plastic to store power more safely than the flammable formulations used in conventional batteries today [47]. Moreover, stretchable piezoelectric devices have been demonstrated to drive a liquid crystal display [48]. On the subject of stretchability and flexibility, Wang *et al.* provide a detailed review of the recent advances in carbon technologies for achieving flexibility in wearable devices [49].

There is also current interest in integrating flexible solar cells in woven fabrics and in clothing [50], with efficiencies reaching 19% for corrugated mono-crystalline silicon cells [51], [52]. However, despite the abundant nature of solar electricity, energy converted from such cells is intermittent and is either location or time dependent. Moreover, the energy density is severely reduced in indoor environments, which means that novel energy harvesting solutions are required.

Based on the above background, there are clearly many challenges associated with the design and fabrication of wearable and implantable technologies for NDs. Advancements in the areas of neurological sciences, integrated circuits, communications and electronic devices (NICE) are necessary to develop these novel devices. We believe that further development in this field can be achieved via carefully structured educational programmes at the postgraduate level. In the next section, we will discuss our methodology in surveying the range of programmes that cover these fields.

III. METHODOLOGY

In this section, we define our research methodology in collecting and synthesizing evidence on neuro-engineering postgraduate programmes using clearly defined criteria. We have recently demonstrated in the literature that there are many traditional engineering undergraduate programmes that provide a basic understanding of neuro-engineering, without providing a sound understanding of communications, signal processing, microelectronics and integrated circuits for wearables and implantables.

Similar to the methodology described in [53] and [16], we first defined the research questions and the inclusion criteria of our search. Second, we selected relevant programmes that met some of these criteria. Third, we analyzed and interpreted our search results. In this case, we defined the following research questions (RQ):

i RQ1: What are the universities that offer these programmes?
ii RQ2: In which countries are these programmes offered?
iii RQ3: How many programmes satisfy all four NICE theme areas?

Based on the above questions, the following inclusion criteria (InC) were defined. Any programmes outside these criteria were excluded:

i InC 1: Programmes are conducted in English;
ii InC 2: Programmes related to one of the NICE themes;

TABLE 1. Descriptors and synonyms used for our search.

Descriptor	Definition	Synonyms
Neuro-engineering	Involves the manipulation of neurons and their sub-cell components to regulate their networks and their function in the nervous system. This eventually controls the functioning of the entire human body. This allows engineers to develop means and tools to control, enhance, or inhibit their function [54].	Neural Engineering
Electronic Devices	Basic building block of all electronic circuits, components and systems [55].	Semiconductor devices
Neuroscience	The study of scientific disciplines related to the nervous system [56].	Neural science.
Integrated Circuits	The interconnection of circuit components consisting of transistors, resistors and capacitors on a semiconductor platform [57].	VLSI.
Communications	A branch of technology concerned with communication via a particular medium [58].	Telecoms, Information Theory, Signal Processing.
Postgraduate Education	Master's degree qualification received after a Bachelor's degree.	Graduate Education

iii InC 3: It is a certified or accredited postgraduate degree programme.

Having defined our research questions as well as our inclusion criteria, we defined our approach in searching for postgraduate programmes. We used "Google" and "findamaster's" portal for our search using the descriptors summarized in Table 1.

Again, similar to the methods using in [16], [53], we developed search strings using Boolean operators (AND, OR) to connect these descriptors.

IV. RESULTS AND DISCUSSION

In the following section we will review and discuss the educational programmes that meet the Inclusion Criteria defined in our Methodology section. From our search, we found that certain programmes tended to focus on a particular thematic area. For example, some programmes offered a cluster of courses on neuroscience or neurotechnology, whereas others tended to focus on communications and signal processing. Therefore, we will discuss our results in terms of the NICE thematic areas. In each thematic area, we will discuss the postgraduate programmes that are relevant to that discipline. First, we will start reviewing the programmes that mainly focus on neuroscience and neurotechnology education.

A. NEUROSCIENCE

According to the Potomac Institute for Policy Studies, Neurotechnology is a rapidly advancing field, with potential impacts that could far surpass those of the information revolution [21]. Education in this area first requires a strong foundation in Neuroscience, which involves teaching the basic principles of the brain and cognition, including neuronal and glial cells functioning and communication in health and unhealthy conditions. Similarly, neurotechnology involves the development of technology and applications, which will feed back into scientific discovery and into the development of products and applications. Examples of engineering programmes with a particular focus on this subject area are shown in Table 2.

Postgraduate educational programmes in Applied Bioengineering and Biomedical Engineering, such as those offered by University of Washington and Politecnico di Milano, train students to apply engineering design to address today's clinical challenges and fulfil the market-based demands of industry and medicine for biotechnology. They provide courses to study the living system, tissue, prostheses, biomedical equipment and instrumentation, information and communications technology (ICT) applications. After these programs students will have learned how to develop new devices, equipment, procedures and systems for prevention, diagnosis, therapy and rehabilitation, learned advanced technological developments in bio- and nanotechnologies and develop innovative materials. More specifically within brain and NDs field of application, master and PhD programs in Neuroengineering provide interdisciplinary courses combining experimental and theoretical neuroscience with profound training in engineering. These courses indeed mesh engineering, mathematics, and computer concepts with molecular, cellular and systems neuroscience.

The Master of Applied Bioengineering (MAB) from the University of Washington allows students to study a set of core courses in Bioengineering, in addition to the ability to specialise in a Technical Concentration Area. The three areas are: Biomedical Imaging, Molecular Bioengineering and Biomaterials as well as Regenerative Medicine and Biomaterials. Moreover, the programme is flexible and allows students to build their own Technical Concentration Area by selecting courses from their department's list of approved electives. In fact, the "Regenerative Medicine and Biomaterials" concentration area offers three electives in the "Neuroengineering" track, which are "Neural Engineering", "Neural Computation and Engineering" and "Neural Engineering Tech Studio". The programme also provides plenty of training opportunities in ICT. For example, courses are available in "Real Time Biosignal Processing", "Medical Imaging", "Computational Bioengineering" and "Computational Systems Biology".

The Bioengineering and Innovation in Neuroscience (BIN) training program by BME Paris, for example, covers human-machine, brain-machine and brain-computer interfaces, the imaging and manipulation of neuronal and brain activity, predictive chemistry for neuroscience, microfluidics

TABLE 2. Programmes with a focus on nice.

Course	Description	Keywords	N	I	C	E	Ref
Applied Bioengineering	1 year MSc program offered by the University of Washington (USA)	Neural Engineering; Neurology; Medical Imaging; BioMEMS	Y	N	Y	Y	[59]
Bioengineering and Innovation in Neuroscience	MSc program offered by BME Paris (France)	Neuroengineering; Machine Learning; Neuroimaging	Y	N	Y	N	[60]
Biomedical Engineering	2 year MSc program offered by Politecnico di Milano (Italy)	Neuroengineer; Electronic Technologies; Biomedical Signal Processing	Y	N	Y	Y	[61]
Biomedical Engineering (Neuroengineering)	2 year MSc program offered by University of Southern California and Viterbi School of Engineering (USA)	Neuroengineering; Biomedical Microdevices; Biomedical Imaging	Y	N	Y	Y	[62]
Biomedical Engineering (Medical device and diagnostic engineering)	3 semester MSc offered by University of Southern California (USA)	Nervous system; Signals and Systems	Y	N	Y	N	[63]
Neuroengineering	Master and PhD programmes offered by University of Utah (USA)	Computational Neuroscience; Statistical Signal Processing; VLSI Design	Y	Y	Y	N	[64]
Life Sciences Engineering with a Specialisation in Neuroscience and Neuroengineering	2 year MSc program offered by Ecole Polytechnique Federale de Lausanne, EPFL (Switzerland)	Neuroscience; Biomedical Signal Processing; Analog Circuits; Flexible Bioelectronics; BioMEMS	Y	Y	Y	Y	[65]
Master of Science and Engineering in Biomedical Engineering	2 year MSc offered by John Hopkins University (USA) with a focus on Neuroengineering	Theoretical Neuroscience; Neural Implants; Sensory Information Processing	Y	N	Y	Y	[66]
Neuroengineering	2 year Elite MSc program offered by the Technical University of Munich (Germany)	Signal Processing; Computational Neuroscience; neurophysiology; Mixed Signal Electronics	Y	Y	Y	N	[67]
Biomedical Engineering - Neuroscience	3 years MSc program offered by the University of Electronic Science and Technology (China) and McGill University (Canada)	Cognitive Neuroscience; IC Design; Bioinformatics; Wearable exoskeleton robot design	Y	Y	Y	N	[68]
Master of Engineering (Biomedical)	3 years MSc program offered by The University of Melbourne (Australia)	Biosystems Design; Circuits and Systems; Sensorimotor Control	Y	Y	N	N	[69]
Master's Degree Programme in Neuroscience	2 year MSc programme offered by the Norwegian University of Science and Technology	Neuroscience; Signal Processing; Neural Networks	Y	N	Y	N	[70]
Biomedical Engineering	1 year MSc by the University of Bristol (UK)	Computational Neuroscience; Digital Filters and Spectral Analysis; Biomedical Imaging.	Y	N	Y	N	[71]
Biomedical Engineering (Medical Device Design and Nano Biomaterials)	3 years MSc program offered by Shanghai Jiao Tong University (China)	Neurongineering; Biomedical Imaging and Image Processing; Neuroscience	Y	N	Y	N	[72]
Biomedical Engineering	1 year master of engineering program only offered to undergrads from MIT (USA)	Neuroscience; Biological Imaging; Electronics and Circuits	Y	N	Y	N	[73]

and other innovative miniaturized biotechnologies for the nervous system, computer modeling of neuronal networks and their applications.

The Master in Life Sciences Engineering with a Specialization in Neuroscience and Neuroengineering provided by Ecole Polytechnique Federale de Lausanne (EPFL) [65] offers courses on neural circuits and behavior, computational neuroscience, human neuroscience, brain dysfunction and neuroprosthetics. It also offers a variety of courses on image processing, machine learning, neural networks and deep learning, which are within the "Communications" track. Moreover, there are courses on "Analog Circuits", 'Flexible Bioelectronics" as well as "Biosensors and Electronic Biochips". Therefore, this programme enables all four NICE thematic areas to be covered.

The Neuroengineering MSE by Johns Hopkins aims to develop new engineering oriented technologies within the medical field for screening, diagnosis, prognosis, rehabilitation, repair, and regeneration, with great interest in brain computer interface, deep brain stimulation, and cell replacement therapy. It also offers courses in machine learning, signal processing, Biomedical Photonics and Neural Implants. Their programme therefore covers three out of the four NICE areas.

The Master and PhD program in Neuroengineering (Neural Interfaces) by The University of Utah's offers research on electrical neural interfaces and neuroprostheses, engineering of neural self-repair, neural plasticity, neural coding in sensory and motor systems, neural imaging, and non-traditional modes of stimulating neural tissue (*e.g.*, focused ultrasound and magnetic stimulation). There are also courses in Information Theory, Digital VLSI Design and Neuromorphic Architectures. However, there were no courses offered in the area of electronic devices [64].

Moreover, the Biomedical Engineering MSc by the University of Southern California offers a special track on "Neuroengineering" [62]. Three courses are available in this track, which are "Neural Implant Engineering", "Computational Neuroengineering" and "Applied Electrophysiology". Moreover, there are plenty of courses that cover the "Communications" thematic area, such as "Integration of Medical Imaging Systems", "Advanced Biomedical Imaging", "Medical Diagnostics, Therapeutics and Informatics

Application'', ''Signal and Systems Analysis'' as well as ''Physiological Signals and Data Analytics''. There is also a special topic on ''Biosensors and Diagnostic Devices for Healthcare Applications''. Furthermore, training in the Electronic Devices thematic area is covered via a course on ''Fundamentals of Biomedical Microdevices''. Therefore, three out of the four NICE areas are covered in this programme.

In addition to Biomedical Engineering, the university offers another MSc in ''Medical Device and Diagnostic Engineering'', which is awarded after three semesters of study [63]. This programme allows students to focus more on ''Product Development'', ''Medical Technology and Device Science'' or in ''Regulation''. Similar to the Biomedical Engineering MSc, this programme offers neuroscience training through courses such as Advanced Studies of the Nervous System and Neural Implant Engineering, as well as a course on ''Signals and System Analysis''. However, from the course titles, no further training is provided in the two remaining NICE areas. Thus, this programme covers two out of the four thematic areas.

The 2-year Neuroengineering MSc by the Technical University of Munich (TUM) offers students plenty of training opportunities in neuroenigneering via courses such as ''Neuro-Anatomy and Neuro-Physiology'', ''Computational Neuroscience'', ''Mixed Signal Electronics in Neuroengineering'', and ''Neuro-inspired Systems Engineering'' [67]. It also provides courses in ''Signal Processing'' and ''Large-Scale Modeling and Large-Scale Data Analysis''. Therefore, the programme covers three of the four NICE thematic areas.

Among the biggest limitations of currently available educational programmes for neuro-engineers, which is of crucial interest for implantable and wearable devices for NDs, involves teaching the regulatory rules of clinical and pre-clinical studies, in particular the principles of laboratory animal science [74]. The final prototype of a wearable or implantable device has to be tested in vivo in animal models in order to be used later in a safe way on humans [75]. Therefore, before devices can be adopted in a clinical context, they need to be tested and proven safe in situations mimicking human conditions using in vitro and in vivo models. For example, cytotoxicity tests provide reliable methods to test the biocompatibility of material used. This helps reduce risks of, for example, skin reactions when wearable devices are used on patients. In vitro tests have to anticipate in vivo tests since they are simpler, faster, more sensible, more reproducible and can help reducing the number of animals used for in vivo tests [76]. In this regard, it becomes important for neuro-engineers to fully grasp the principles of in vitro and in vivo models, what rules have to be followed for laboratory animal use in research, have a basic knowledge of toxicology, brain immune responses, and brain pathology.

As specifically detailed in the methodology section, we focused our search on devices for NDs. We will therefore discuss degree programmes with a focus on other NICE areas in the following sections, in addition to neuro-engineering or neuroscience education.

B. INTEGRATED CIRCUITS

Integrated circuit design education involves teaching the basic principles of low power circuits and embedded systems. The aim of this track is to develop models that mimic brain networks. Neuromorphic models of the cerebellum have been developed in the literature [22], [77]. Progress has also been made in developing an artificial hippocampus (*e.g.*, brain model incorporated on a chip) [78], [79]. Examples of programmes in this track are shown in Table 2.

According to our review, there is a limited number of programmes that provide dedicated training in neuroscience or neurotechnology with IC design. The 3-year Biomedical Engineering programme between the University of Electronic Science and Technology of China (UESTC) and McGill University provides neuroscience training via two-credit courses that include ''Fundamentals of Brain Science'' and ''Cognitive Neuroscience''. Moreover, this programme offers Communications-related courses on ''Stochastic Processes and Applications'', ''Bioinformatics'', ''Digital Communications'' and ''Digital Signal Processing''. It also offers an optional course on ''IC Design''. However, there are no courses in the area of Electronic Devices.

The programme offered by the University of Melbourne is a 3-year Master's degree. The programme offers a variety of modules in ''Circuits and Systems'', as well as ''Biosystems Design''. It also offers a module on ''Anatomy and Physiology for Engineers'', which deals with the principles of sensory motor control.

Moreover, the previously mentioned Neuroengineering programme by TUM provides training in Integrated circuits via a dedicated course on ''Mixed Signal Electronics in Neuroengineering'' [67]. The course provides state-of-the-art training in the design and fabrication of soft and flexible neuroelectronic interfaces. It also enables students to deal with analog, digital and mixed signals in an implantable or wearable system.

Furthermore, the Life Sciences in Engineering MSc by EPFL offers training opportunities in IC via courses such as ''Analog Circuits for Biochip'', which mainly focuses on introducing students to analog CMOS design for biosensor applications [65].

C. COMMUNICATIONS AND SIGNAL PROCESSING

This track involves information traveling between the brain and external tools. Engineers are required to develop a new generation of signal collection devices and technologies, to understand and decode brain signaling. Current Communications and Signal Processing educational programmes typically merge the concepts of wired and wireless communication networks with the classical domains of signal processing, such as image, audio, video and biomedical signal processing. To that end, advanced mathematical optimization and artificial intelligence/machine learning are key techniques. The combination of these domains leads to applications in areas such as sensor design, multimedia systems, wearable technologies, biomedical signal processing, brain/computer interfaces, big data, and many other.

The role of signal processing and communications receives increasing importance in the field of neuroscience with the increase of complexity and scale in neural recordings. Neural signal processing inherits disciplines that combines statistical signal processing, statistics, control and optimization methods to process neural or neuronal data. Nevertheless, unlike traditional signal processing assumptions, neurophysiological signals are often non-Gaussian, non-stationarity and heterogeneous [39]. In addition, due to recent advancements in machine learning techniques, the functionality of low power and lightweight wearable devices can now be augmented using these algorithms.

Table 2 shows programmes with a focus on communications and signal processing, with applications connected to neuroscience. For instance, at the Technical University of Ilmenau [80], in Germany, offers a master of science programme in communications and signal processing that can be specialized towards neurological signal processing, brain/computer interfaces, medical scans, *etc*. Similarly, the University of Edinburgh [81], UK, has a curriculum that covers both signal processing and communications, with a strong emphasis on machine learning techniques, which can be specialized towards neurological applications.

In addition, the Master's Programme in Neuroscience at the Norwegian University of Science and Technology [70] includes the fundamentals in neuroscience as their compulsory courses, while elective disciplines can be chosen in order to focus on signal processing for neurological applications. Furthermore, the MSc programme in Biomedical Engineering at University of Bristol [71], UK, focuses on computational neuroscience, merging skills in digital filters, spectral analysis and artificial intelligence in order to solve biomedical and neurological applications.

There are many other interesting biomedical engineering programmes with a focus on signal processing or communications. For example, the two year Master's programme in Biomedical Engineering by the University of Oulu, which has a strong focus on biomedical signal and image processing, machine learning, and measurement and analysis of biomedical data [82]. However, this programme offers no training in neurological sciences, which is why it has been excluded from Table 2.

Furthermore, the Master's programme in Biomedical Engineering by Shanghai Jiao Tong University (China) [72] provides interdisciplinary training in biology, medicine and engineering. There are no details regarding the courses offered. However, the advertised programme indicates that training in ''Neuroscience and Neurongineering'', as well as ''Biomedical Imaging'', ''Image Processing'', ''Biomedical Signal Processing and ''Brain Functional Imaging''.

Other neurotechnology programmes with a focus on information technology, or the Communications theme include MIT's Master of Engineering (MEng) in Biomedical Engineering [73]. However, this programme is only offered to MIT students and provides plenty of opportunities for students to study neuro-engineering topics, such as Principles of ''Neuroengineering'', ''Cellular Neurophysiology and Computing'', ''Neurotechnology in Action'', ''Principles and Applications of Genetic Engineering for Biotechnology and Neuroscience''. Furthermore, it offers graduate training in ''Biomedical Signal and Image Processing'', ''Imaging and Sample Processing in Biology and Medicine'' and ''Medical Imaging Sciences''.

Moreover, as previously mentioned in Table 2, the 2-year Biomedical Engineer MSc offered by the Po-litecnico di Milano [61] also provides two separate tracks for specialisation in either Information Bioengineering (BIF) or Electronic Technologies (BTE). The Information Bioengineering track aims to provide training from the ICT field, so that graduates can effectively manage information systems and networks for healthcare organizations, support clinical decisions, assess service quality in healthcare, design algorithms for processing biomedical data and to develop bio-inspired intelligent systems.

Furthermore, the previously mentioned MSc by BME Paris [60] offers a dedicated course on ''Brain-Computer Interfaces'', which aims to provide knowledge in signal processing and machine learning techniques. Subject to approval, the Bioengineering and Innovation in Neuroscience (BIN) track also enables students to take course from other tracks, such as ''Machine Learning for Bioimaging'' and ''An introduction to Virtual Reality and Augmented Reality''.

Finally, other programmes in Table 2, such as [59], [62], [65]–[68], also involve at least one discipline, either mandatory or elective, in basic signal processing applied to biomedical engineering. Among these, it is worth mentioning the MSc in Neuroengineering at the John Hopkins University [66], in the US, with strong emphasis on artificial intelligence, sensory information processing and machine learning disciplines applied to neuroengineering.

D. ELECTRONIC DEVICES

Semiconductor devices have come a very long way since the invention of the point contact transistor in 1947. These tiny devices will transform and shape our lives in ways we have yet to discover. The pn-junction diode is the basic building block of all electronic devices. Important electronic devices such as MOSFETs, BJTs, Solar Cells and LEDs all consist of this basic block. They are used in energy harvesters, as well as key electronic components found in power conditioners and energy management circuitry.

However, semiconductor devices are rigid, whereas the human body is soft and curvilinear [83]. Consequently, new devices based on alternative materials need to be developed for implants and wearables to be used for neurological purposes. Biocompatible and flexible transistors, light-emitting diodes, photodetectors and electrodes need to be developed. For example, the development of new sensors for assessing brain behaviour is necessary. Moreover, engineers need to develop new brain signal input/output (I/O) devices with

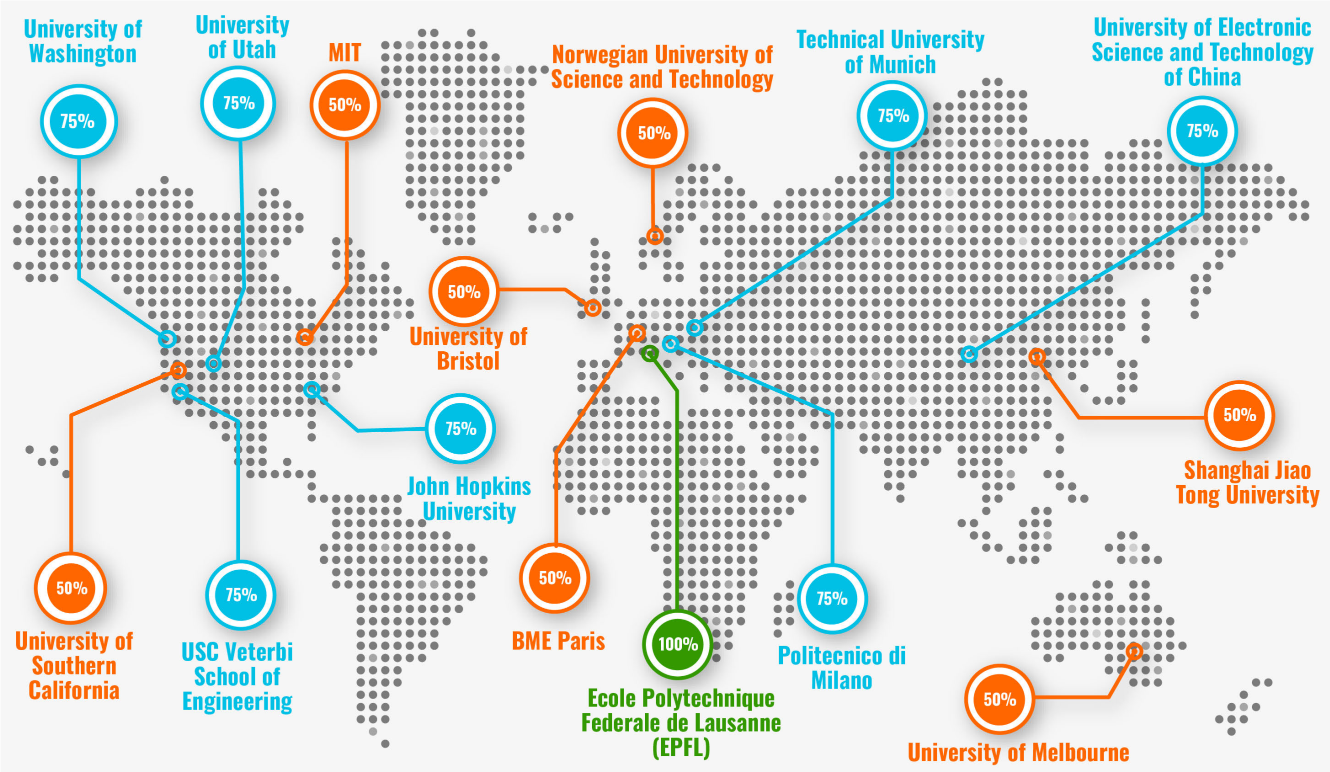

FIGURE 4. Location of Neuroengineering programmes that satisfy the NICE areas. Each institution was given a score according to how many of the NICE areas were covered.

greater scope and function (extending and refining technologies like deep brain stimulation, neuromodulators).

The programme previously mentioned Biomedical Engineer MSc by the Politecnico di Milano offers a dedicated track on Electronic Technologies. This track provides training in electronic and information methods concerning sensors, biosensors, micro-technologies, measurement chains, interfacing with biological systems and modelling [61].

Moreover, there are a number of undergraduate programmes with a focus on electronic devices. For example, the undergraduate MEng programme by the University of Southampton offers a number of modules on Semiconductor Devices, Microfabrication, Microsensor Technologies, VLSI Design and Solid State Devices [84]. This programme also includes training in neuroscience, since a course on Principles of Neuroscience is offered to undergraduates in the third year of study.

Furthermore, TU Delft offers a Master's programme in Biomedical Engineering with three tracks for students to choose from [85]. One of the tracks is in Neuromusculoskeletal Biomechanics, another is in Medical Devices and the third is in Medical Physics. The Medical Devices provides plenty of training opportunities in Implantable Biomedical Microsystems, Biomedical Electronics as well as Sensors and Actuators. However, this track provides no training in neuroscience nor neurotechnology, which is why it was excluded from the list. Similarly, the one year master's in Advanced Chemical Engineering with Healthcare Technology offered by the University of Birmingham offers training in energy harvesting technologies for healthcare [86]. However, the programme is missing modules on neuroscience or neurotechnology, which is why it was again excluded from our list.

Finally, the MAB programme by the University of Washington also offers some opportunities for students to receive training in the Electronic Devices track [59]. For example, courses on "BioMEMS" and "Biosensors and Biomedical Sensing" are provided.

V. DISCUSSION

Based on the data collected in Table 2, a percentage score was given to each higher education institution (HEI). This score indicated how well all four NICE areas have been covered by each of the compiled HEIs. Consequently, a map showing the location of the institutions offering neuroengineering education with a focus on any of the NICE areas was developed, as shown in figure 4. Clearly, the majority of the HEIs providing neuroengineering education for implantable and wearable electronics are located in Europe and in the US. Only one HEI covered all four thematic areas, which is located in Europe.

Moreover, figure 5 shows statistical data. According to the data, the mean score of all HEIs was 65%. Consequently, three European HEIs achieved scores higher than

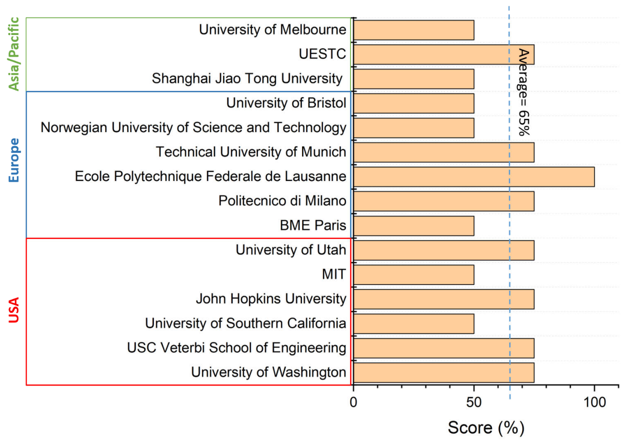

FIGURE 5. **Statistical data showing HEI scores. European HEIs lead global scores in neurongineering education.**

this average, whereas four institutions from USA achieved higher scores. Again, this further demonstrates that European and US institutes offer a more varied and expert training in neuroengineering for implantable and wearable electronics education.

From the results in the previous section, as well as the map shown in figure 4, it is clear that the majority of the neuroengineering programmes that meet or partially meet all four NICE areas are located in Europe and the US, with only a handful in the Asia-Pacific region. As demonstrated from figure 5, we have compiled six programmes in Europe, two in China, six in USA and one in Australia. Moreover, only one neuroengineering programme covers all four NICE topics, which is offered by EPFL in central Europe.

Moreover, three European HEIs achieved scores exceeding the mean score of 65%. These institutes include the Technical University of Munich (TUM), Politecnico di Milano and EPFL. Furthermore, EPFL achieved a perfect score of 100% since it managed to provide courses and training that covered all four NICE areas. On the other hand, John Hopkins University, the University of Utah, the University of Washington and the 2-year MSc offered by USC Viterbi School of Engineering from the United States provided training that exceeded the mean cohort scores (75%). Otherwise, all other HEIs in our study covered at least two out of the four NICE thematic areas.

It is noteworthy to mention that, despite the proliferation of NDs in North Africa and Asia, there are no educational programmes that meet the needs of these communities. Therefore, cross border efforts are required to ensure that these countries have the necessary expertise to deal with these issues. Since expertise in this area is mainly located in Europe, a possible solution could be the development of a multi-country capacity building project funded by the Erasmus Plus programme [87]. Among the aims of such programmes is to transfer know-how from European programme countries to a variety of partner countries that include the North Africa region. There are many successful programmes that have been initiated through this scheme, such as the Solar Energy System Design using Advanced Learning Aids (SOLEDA) project [88].

In terms of subject content, we identified the disciplinary areas that needed to be covered to develop the next generation of neuroengineers in NDs. However, how will these engineers be taught? What teaching and learning methods will be adopted? Behavioral scientists have settled on the proposition that learning is the result of active behavioral experience that is combined with swift feedback [89], [90]. The speed of learning is therefore dependent on the quantity of experience and the quality of feedback that can be produced over time [90]. In future, perhaps wearable devices can be used to detect biomarkers in the brain, informing instructors whether students have grasped the learning materials or not [91].

As previously mentioned by Donald Clark [92]: "When we know what you think, we know whether you are learning, optimise that learning, provide relevant feedback and also reliably assess. To read the mind is to read the learning process. A window into the mind gives teachers and students unique advantages in learning."

In addition to the use of these wearable devices to monitor student progress, ICT tools can be used to support the supervision of these students remotely [93]–[95]. Moreover, active learning techniques can be introduced. As previously mentioned in the literature, active learning techniques have demonstrated improved student learning [96]. Adopting or applying learning techniques that mimic the environments in which engineers will be exposed to is important [97]. For example, Team Based Learning and Project Based Learning have been introduced in the literature to promote collaborative learning [98]–[100].

VI. CONCLUSION

The aim of this article was to review the range of postgraduate educational programmes designed to train neuroengineers in implantable and wearable electronics for ND applications. We have identified four key areas that need to be covered for graduates to obtain this expertise. These areas include Neuroscience, Integrated Circuits, Communications and Electronic Devices. We referred to these disciplines as the NICE areas. Following our review, we have identified a total of 15 higher education institutes that cover or partially cover these disciplinary areas. Almost half of these institutes are located in Europe. Furthermore, three of these European institutes covered at least three out of the four NICE areas, which include the Technical University of Munich (TUM), École Polytechnique Fédérale de Lausanne (EPFL) and Politecnico di Milano. One of these European institutes provides training that covers all four areas, which is EPFL. Therefore, although European and US HEIs are in a stronger position regarding educational programmes in NDs, there is clearly room for further improvement.

Nevertheless, our investigations have focused entirely on surveying English speaking programmes. Therefore, other postgraduate programmes in Europe or Asia may exist in other countries, which may have been excluded from our list.

Furthermore, since none of these programmes are provided by HEIs located in regions with high risk of NDs, we proposed the development of transnational curricula via programmes that foster cross-border collaborations, such as those between European universities and those located south of the Mediterranean. We have also provided recommendations regarding the teaching methods that ought to be adopted to deliver such innovative teaching programmes. Rather than relying on traditional teaching methods, we recommend the use of wearable technologies, ICT technologies as well as active learning methods.

ACKNOWLEDGMENT

This work was supported by UK's Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/R511705/1. It was also supported by CAPES, Finance Code 001, and CNPq.

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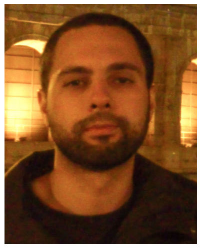
RAMI GHANNAM (Senior Member, IEEE) received the B.Eng. degree in electronic engineering from King's College, and was awarded the Siemens Prize, and received the DIC and M.Sc. degrees from Imperial College London, and the Ph.D. degree from the University of Cambridge, in 2007. He is currently a Lecturer (Assistant Professor) in Electronic and Nanoscale Engineering with the University of Glasgow. He held previous industrial positions at Nortel Networks and IBM Research GmbH. His research interests are in energy harvesters and engineering education. He is a Senior Fellow of Glasgow's RET Scheme and serves as Scotland's Regional Chair of the IEEE Education Society.

GIULIA CURIA received the Ph.D. degree in physiology from the University of Milano, Italy, in 2004. After many years of international experience (Canada and USA) as a Postdoctoral Fellow, she won the prestigious "Rientro dei Cervelli" program and joined the University of Modena and Reggio Emilia, Italy, in 2010, becoming an Associate Professor of Physiology, in 2014. She is the Head of the Experimental Electroencephalography and Neurophysiology Laboratory. She has authored 29 articles in peer-reviewed journals and one book chapter. She is a project reviewer for international foundations such as the European Commission, and an article reviewer for several international journals in the neuroscience and physiology field.



GLAUBER BRANTE (Senior Member, IEEE) received the D.Sc. degree in electrical engineering from the Federal University of Technology–Paraná (UTFPR), Curitiba, Brazil, in 2013. In 2012, he was a Visiting Researcher with the Institute of Information and Communication Technologies, Electronics, and Applied Mathematics, Catholic University of Louvain, Belgium. He is currently an Assistant Professor with UTFPR. His research interests include cooperative communications, HARQ, energy efficiency, and physical layer security. He was a recipient of the Best Ph.D. Thesis Award in electrical engineering in Brazil in 2014. He was a co-recipient of the 2016 Research Award from the Cuban Academy of Sciences. He was the Co-Editor-in-Chief for the *Journal of Communication and Information Systems* from 2018 to 2020. Since 2018, he has been serving as an Associate Editor for the IEEE Communications Letters. Since 2019, he has been serving as an Associate Editor for the IEEE Open Journal of the Communications Society.

SARA KHOSRAVI (Student Member, IEEE) received the B.S. degree in management and the M.S. degree in international business and economics from the University of Pavia, Italy, in 2013 and 2016, respectively. Her M.S. dissertation was about the impact of renewable energy on electricity, heat, and transport in the U.K. She is currently pursuing the Ph.D. degree in engineering education with the University of Glasgow, U.K. Her research interests are in engineering education, which includes investigating innovative learning and teaching using wearable devices.

HUA FAN (Member, IEEE) was born in Ziyang, Sichuan, China, in 1981. She received the B.S. degree in communications engineering and the M.S. degree in computer science and technology from Southwest Jiaotong University, Chengdu, China, in 2003 and 2006, respectively, and the Ph.D. degree from Tsinghua University, Beijing, in July 2013. From September 2013 to June 2016, she was an Assistant Professor with the University of Electronic Science and Technology of China. Since July 2016, she has been an Associate Professor with the University of Electronic Science and Technology of China, Chengdu. Her research interests include low-power, high-speed, and high-resolution A/D converter designs. From March 2015 to March 2016, she joined the Integrated Microsystem (IMS) Research Group, Department of Electrical Computer and Biomedical Engineering, University of Pavia, Italy, holding a postdoctoral position, under the supervision of Prof. Franco Maloberti. She has been the recipient of several awards, including the Best Oral Presentation Award from the IEEE Asia Pacific Conference on Circuit and Systems (APCCAS) in 2018, the China Scholarship Council (CSC) Support in 2015, among others. She has authored over 50 articles in peer-reviewed journals, i.e., IEEE Transactions on Circuits and Systems I, IEEE Transactions on Circuits and Systems II, IEEE Access, among others), and also in international conferences.