DESIGN OF A RECONFIGURABLE POWER-ADAPTIVE HIGH-RESOLUTION NEURAL DATA COMPRESSION ALGORITHM

By

Mohammed Ashraf Hassan

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
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in
Electronics and Communications Engineering

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Design of a Reconfigurable Power-adaptive High-Resolution Neural Data Compression algorithm

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Summary:

In this thesis, five different proposed low-power image compression algorithms based on discrete cosine transform (DCT) and discrete wavelet transform (DWT) are investigated and compared to provide the best trade-off between compression performance and hardware complexity. Finally, harvested power adaptive high-resolution neural data compression is introduced to control the compression algorithm according to available harvested power. Hence, maximum signal to noise and distortion ratio (SNDR) is achieved based on the available harvested power without any data loss.

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Table of Contents

List of Tables

List of Figures

Nomenclature

MEMS	Micro-Electro-Mechanical Systems
EEG	Electroencephalography
DCT	Discrete Cosine Transform
DWT	Discrete Wavelet Transform
2D-DCT	Two Dimension Discrete cosine Transform
2D-DWT	Two Dimension Discrete Wavelet Transform
ECOG	Electrocorticography
EEG	Electroencephalography
JPEG	Joint Photographic Experts Group
SNDR	Signal to Noise and Distortion Ratio
HW	Hardware
HDL	Hardware Define Language
DFT	Discrete Fourier Transform
MJPEG	Motion Joint Photographic Experts Group
FOM	Figure of Merit
ASIC	Specific Integrated Circuits
RAM	Random Access Memory
PV	Photovoltaics
RF	Radio Frequency
PZT	Lead Zirconate Titanate
IOT	Internet of Things
TX	Transmitter
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
IP	Internet Protocol

Abstract

Nowadays, brain scientific research progress depends on signal compression at high spatial resolutions, for low-rate transmission through wireless connection to the outside world and efficient storage. Without data compression, these data rates would conflict the neurophysiologic restrictions in terms of low energy and low area consumption. So that neural data compression at the implant site is substantial in order to conform with the wireless rates restrictions. In this thesis, the high spatial correlation is utilized to increase the data compression ratio. Then, five different proposed low-power image compression algorithms based on discrete wavelet transform (DWT) and discrete cosine transform (DCT) are investigated and compared to provide the best trade-off between compression performance and hardware complexity. Hence, the Adaptive 2D-DWT algorithm is deduced as a promising solution for low-power implantable devices.

Furthermore, current treatment devices need the complete waveform and history for every electrode to be extracted instead of extracting the special signal features only to be able to detect and diagnose neural brain disorders. So that it must be guaranteed that the detected neural data can be transmitted continuously without any stops or data loss and also it must be guaranteed that the compressed data can be decompressed at the other side with high quality without significant distortion. In this thesis, the neural compression algorithm is adapted according to the available harvested power budget. Therefore, the maximum signal to noise and distortion ratio (SNDR) is achieved based on the available harvested power budget without any data loss.

Chapter 1 Introduction

1.1. Background

Over the last 40 years, implantable electronic devices and systems have faced a significant transformation, becoming a valuable biomedical tool for measuring, monitoring and stimulation physiological responses using wireless communication. The discovery and posterior advancement of these devices have relied heavily on the growing knowledge related to various aspects of the human neuro system, and the development of electronics technologies capable of interfacing with living tissues and organs at microscale and nanoscale. Increasing in stability, miniaturization and lower power requirement of modern electronics led to a plenty of miniature wireless electronic devices, such as sensors and intelligent gastric, implantable cardioverter defibrillators, implantable cochlear, and deep brain, nerve, and bone stimulators are implanted in patients worldwide [29,30,31,32]. Advances in semiconductor technology, particular in the area of micro fluidic lab-on-chip biomedical systems and micro-electro-mechanical systems (MEMS) have allowed for the development of units for rapid diagnostics, and precisely controlled pulsatile, sustained or rapid delivery of complex therapeutics and drugs [33].

Furthermore, these devices are used for the development of tissue engineering platforms and also have been used in regenerative medicine applications, particularly where nervous and muscular tissues are concerned. In addition to growing the survival rate and the life quality of patients globally, implantable electronic devices have contributed significantly to assessment of the biological processes taking place within the human body, including the hard mechanisms of neural control and communication, and greatly enhanced the understanding of how these are affected by various diseases and remediation. Ex MEMS and dielectric elastomer actuators have been used to explore the manner in which biological cells modulate their behavior, proliferate or differentiate in response to electrical and mechanical stimuli, knowledge which is fundamental for adequate tissue engineering design [34]. In addition to playing a deep role in the progress of biomedical sciences and regenerative medicine, communication technologies and implantable information drive memorable changes in the cultural and social attitudes of people towards technology. There, implantation is viewed beyond the medical context as a means to promote the experiences and abilities of healthy individuals. Despite of essential innovations in the application and fabrication of implantable biomedical electronic systems since the first implantable heart pacemakers, the modern implants are still faced with a number of challenges [35].

In terms of device production, there is a strong trend to produce devices with ever size and weight in order to make them compatible with normal human activities and enhance leisure for the host. Implants that weight less than 1% of the patient's body weight are typically required. When used whether single-use batteries or rechargeable batteries significantly contribute to the overall dimensional size and weight of the device. Rechargeable batteries, like those are used in cochlear implants, can be recharged transcutaneously using external signals, e.g., pizoelectricaly, radio frequency (RF), ultrasound, infrared light, low-frequency magnetic field, and so on. More recently, internal charging using the energy produced by the physiological environment or natural body motion has been investigated. Single-use, non-rechargeable batteries, like those are used to support pulse generation in deep brain stimulators and cardiac pacemakers, have a predetermined lifetime, at the end of which they have to be surgically replaced, at high cost to the patient and the healthcare system. Further miniaturization can be earned by means of battery-less implants, where energy harvested from natural or artificial power sources surrounding the patient is used directly to power the device [36]. Inductive and electromagnetic coupling are extremely used to power remotely battery less devices. In the former case, time-harmonic magnetic field generated by the low frequency alternating current in the external coil generates an alternating current in the implanted component, whereas in the latter, electromagnetic waves are generated from the antenna in the far field region to power the implanted chip. Biomedical actuators that do not base on the harvesting, traditional wireless delivery, accumulation and storage of power in electrical form have been explored for such high-energy actuation applications as mechanical adjustment in implantable devices and drug release.

At the same time, there is a strong emphasis on increasing the functionality and reliability of these electronic devices to support complex real-time stimulation, data collection, data compression and reliable wireless data transmission to external world. This increasing complexity of signal processing electronics further increases the power budget of the device, which should remain very low if the device is remaining working for extended periods of time. For instance, a wide band technology offers high speed data transfer between the implanted devices, e.g., implantable electronic cardiovascular devices, low interference potential and the medical practitioner, yet its implementation is limited due to its high power consumption.

The ability of the implanted devices, such as glucose monitors, pacemakers, and insulin-delivery systems, smart prosthetics, and neural stimulators, to be easily interrogated by health practitioners also makes these systems susceptible to hacking [37]. In addition to having access to secret patient data, the systems can be reprogrammed, interfering with the correct device operations. Therefore, firewalls, including security check protocols, security measures, restricted network access and data encryption should be seriously considered.

Application of molecular-scale and nano-scale technologies for fabrication and design of the implantable circuits can lead to remarkable progress in power dissipation and integration density, enabling nano-biorobotics and neuroelectronic interfacing. However, current biomedical technologies are still faced with challenges, like relatively high standby power consumption, lower reliability, and electron leakage due to insufficient insulation.

Furthermore, in an effort to improve the resolution of the collected biological signals, the increasing number of electrodes demands more energy to be delivered to the electrode array, thus potentially growing the thermal energy dissipated within the implant circuitry. Given the high cost and time associated with the surgical implantation of the device and the recovery of the patient, long-term reliability of the device is fateful.

The drive towards small, light and flexible devices may reduce mechanical robustness of the implant; offensive cleaning procedures used on the devices prior to implantation may further contribute to weakening of the organic layers. The ensuing in loss of integrity and vivo degradation may be harmful to the performance of the system, leading to the system failure, e.g., subsequent surgical removal and electrical shorting. The implanted device and its degradation by-products may stimulate activation of a range of invulnerable mechanisms, leading to inflammation, which in turn may further contribute to the implant degradation.

Achieving suitable biocompatibility is a hard matter, due to the dynamic multifaceted nature of the host biological response to synthetic and organic materials used in device fabrication. Where in vivo stimulation or sensing is required for a short period of time, resorbable implantable electronic systems can provide a solution to overcome inflammation and infections associated with long term implant utilization. The premise is that the materials used in system fabrication are biodegradable and undergo controlled dissociation over time under normal in vivo physiological conditions. The degradation by-products forbidden minimal toxic response and are removed from the peri-implantation site by means of normal metabolic activity [39]. However, fabricating a high performing electronic device from entirely biodegradable, non-toxic set of materials is a difficult undertaking, particularly at small scales. A combination of reliable and robust non-biodegradable silicon electronics with bioresorbable polymer platform offers both sufficient bulk degeneration and the flexibility of the device that the invulnerable response to the remaining material is minimal [40].

For the technology to be clinically implemented, however, the challenges associated with integration of sensitive electronics functions with the fabrication techniques used for production of biodegradable component, and the control over degradation kinetics and biocompatibility of the device should be addressed. In spite of many reports detailing the biological activity and degradation behavior of many commonly used materials in vitro and in vivo, the appreciation of these complex processes is yet to be adequate. The aim of this background is to discuss the challenges faced by modern implantable electronic systems and give a brief overview of the solutions that have been proposed, investigated and implemented in order to overcome these challenges.

When designing an implantable electronic device, several general requirements need to be addressed, namely minimal weight and size, low power consumption, high reliability, high data rate and data latency. As the case with any commercial product, the design of the implantable systems is heavily influenced by the demands and preferences of their consumers.

In addition to being less invasive to the patient body during the implantation, lighter and smaller devices are likely to result in less pain and discomfort to the host during recovery and use. The extravagant size and weight may be harmful to the recovery process by putting pressure on the adjacent tissues that have already been damaged as a result of surgery, contributing to the inflammatory processes within the peri-implant space. Light and small devices are less restrictive in terms of normal level of human activity, and thus sustain better quality of life to the patients. The power source and encapsulation components remain the major contributors to the overall size and weight of the device, whereas the electric circuitry components have decreased dramatically with the advancements in nanotechnology and MEMS. Coupling capacitors used to ensure charge balance and effectively minimize current leakage may further increase the volume of the implantable module. Lower power consumption is important in terms of both the long-term performance of the device and the safety to the patient.

Furthermore, the power use by interface electronics should be minimized to ensure longevity of the implants with single-use batteries, as the replacement of such a device would require a costly and invasive surgical procedure. Although using a rechargeable battery may require the need for battery replacement surgical interference, the need for frequent charging may be inconvenient, resource-consuming activity and time-consuming.

Electrocorticography (ECoG) is a type of electrophysiological monitoring that uses electrodes placed directly on the naked surface of the brain to record electrical activity from the cerebral cortex. But, conventional EEG electrodes monitor this activity from the exposed surface of the cortex (outside the skull). ECoG can be performed either extra operative ECoG (outside of surgery) or intraoperative ECoG (during surgery in the operating room). Because a surgical incision into the skull (craniotomy) is required to implant the electrode grid, ECoG is an invasive procedure.

Electrocorticography (ECoG) signals are composed of local field potentials, recorded directly from outside the skill. The potentials occur primarily in cortical pyramidal cells, In addition, thus should be conducted through several layers of the cerebral cortex, arachnoid mater and cerebrospinal fluid before reaching subdural recording electrodes (placed just below outer cranial membrane). However, to reach the scalp electrodes of a conventional EEG, electrical signals should also be conducted through the skull, where potentials rapidly reduce due to the bone low conductivity. Hence, the Electrocorticography (ECoG) spatial resolution is higher than conventional EEG, a critical imaging advantage for presurgical planning [41].Electrocorticography has a spatial resolution of 1 cm and a temporal resolution of approximately 5 ms [42]. Using depth electrodes, the local field potential gives a measure of a neural population in a sphere with a radius of 0.5:3 mm around the tip of the electrode [17]. With a sufficiently high sampling rate (more than about 10 kHz), depth electrodes can also measure action potentials. In which case the spatial resolution is down to individual neurons, and the field of view of an individual electrode is approximately 0.05-0.35 mm [17].

Nowadays, electroencephalogram classification has become an important problem in several fields. In the medicine field, EEG detection could be incredibly promising for stroke or seizure detection in patients that are oversensitive to such conditions, and a great deal of research has already been put into solving this problem. Other medical applications include manufacturing transportation devices for patients with limited motor abilities to control using simply their thoughts or extremely tender facial movements. Both of these will pick up EEG and an accurate and classifier will lead to successful creation of such a system which would change the patients’ lives with such a failure. Yet other neuroscience and psychology applications, Electrocorticography classification can give insight into the human brain inner workings.

In the biomedical engineering field, neural data recording has a considerable importance especially by employing neuroprosthetic devices and brain machine interfaces. Furthermore, multichannel neural recording is essentially for bio analysis and is commonly used. However, recording big amounts of data has been a challenging task; for example, a typical recording experiment in which data is obtained from a 1024-channel electrode array at the rate of 64 kHz per channel with 12-bit precision yields a data rate of around 768 Mbps, which is much beyond the capacity of state-of-art wireless links that are used in neural applications. Wireless transmission and reception are used for conducting experiments on freely behaving primates and animals. Another important requirement in a neural recording system is that it must be able to operate with a low power. All neural chips which are implanted in living human bodies must be able to operate at a very low power (less than or equal to 8–10 mW), failing would lead to temperature increasing (exceed 1°C) and cause damage of neural