Distributed Intelligent Sensor Network for Neurological Rehabilitation Research

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Erklärung

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Abstract

This work introduces a distributed intelligent sensor network for neurological rehabilitation, designed to address clinical needs of patients with Parkinson's Disease (PD). Frequently, PD patients suffer from tremor at rest, rigidity, bradykinesia, and postural instability. Furthermore, there is often reduced coordination between respiration and locomotion, i.e., footsteps are in coordination with respiration in healthy subjects, whereas this coordination is disordered or even absent in PD patients. Monitoring and assessment of the coordination provides interesting insight into PD neurological rehabilitation: can the level of this coordination be an index for which the health status or rehabilitation progress of PD patients is gauged? Can improving this coordination promote rehabilitation of PD patients? Resolution of these issues requires a mobile sensor network system, which allows long-term monitoring of these vital signals, along with real-time analysis of the respiration-locomotion coordination during rehabilitation. This system may facilitate the assessment of therapeutic effects for PD, as well as the patients' health status.

This system should satisfy the following requirements: ensure patient comfort through miniature form-factor; low-power operation to allow for an extended period of operation without battery exchange; continuous monitoring of vital signals and autonomous measurement; lossless continuous data acquisition and storage on sensor; real-time signal processing, including detection of step events and determination of respiratory phase; communication between devices, as well as data exchange with a PC for the system configuration, data visualization and further analysis.

A number of ongoing projects have contributed to establishing proactive and unobtrusive body sensor network systems. For example, a range of wireless medical sensors has been developed based on the popular TinyOS hardware platforms. However, physical access to the commercial system can be extremely limited, thus hindering the adaptation of these systems for this project. Advances in wearable health systems have resulted in a variety of prototypes integrated with textile sensors. These systems integrate a data-logger to acquire raw data, which can then be sent to a remote expert center. Nevertheless, on-sensor processing is required to allow bio-feedback applications in the future.

To meet the needs stated above, a distributed wireless communicating network of sensor nodes composed of intelligent Network Operating Devices (iNODE) has been developed. It focuses on the long-term monitoring and analysis of the respiration-locomotion coordination for PD patients. The sensor network system incorporates portable and patient-comfortable electronic sensors for sensing the vital signals with sensor nodes based on a microcontroller. The iNODEs include analog signal conditioning circuits connected with the sensors, thus allowing for lossless data acquisition, storage, and real-time signal processing on the sensors. A wireless solution based on IEEE 802.15.4 standard has been developed

for data transmission within the sensor network and communication between the sensor network and the PC. The prototype of iNODEs can be folded into a 20x20x20mm cube. The compact size, along with flex-PCB and wireless design helps improve patient comfort. Ultra low-power electronics in the system allow for 24/7 recordings with lightweight Li-Ion batteries. The modular system conception enables different physical sensors to be easily plugged into the iNODEs, thus extending the possibility of further applications to be developed for this system. This dissertation describes the design of a system solution in cooperation with clinical partners, the search for suitable sensors according to the specifications, the process of integration of the sensors into the iNODE system, the development of the signal-conditioning circuits, the design of the real-time signal processing algorithms for feature extraction, and implementation of the algorithms on the iNODE-platform based on the microcontroller. In addition, preliminary tests of the system have been carried out in clinical setting successfully.

The dissertation is divided into six chapters:

1. Introduction: clinical context (including pathology of PD), clinical applications of the sensor network, clinical and system design requirements and the conceptual design of the iNODE system.

2. Methods for step detection: review of frequently-used methods for step detection and its theoretical background.

3. Methods for respiratory monitoring: review of techniques for non-invasive assessment of respiration with sections on calculation of respiratory phase and coordination between steps and respiratory phase.

4. The iNODE system: hardware platform, wireless communication, software structures and fixed-point algorithms for real-time signal processing.

5. Results: evaluation of signal-processing algorithms using clinical data and results of real-time implementation of the algorithms.

6. Summary and perspectives: conclusions and recommendations for future research.

The dissertation encompasses a wide scope of technical disciplines: sensor technology, electronic circuit design, signal processing algorithms, embedded system (including both software and hardware), as well as wireless communication. It explains step detection and phase determination from theoretical and practical standpoints. Major components and processes of the development of the sensor network system for the clinical application are described in detail in the dissertation. In the next stage, this system will be tested in a clinical setting of occupational therapy involving PD patients on a treadmill. After the evaluation of this stage, further studies using this mobile wireless system will be conducted for long-term recording during daily life.

Contents

Abbreviations and Acronyms

ADC	analog-to-digital converter
AM	amplitude modulation
aNODE	autonomous Network Operating DEvice
ANS	autonomic nervous system
CAP	contention access period
CDM	peak-detection method based on combined dual-axial signal
CFP	contention-free period
CNS	central nervous system
CPU	central processing unit
DMA	direct memory access
DAQ	data acquisiton
DC	direct current
DCO	digitally controlled oscillator
DFT	discrete Fourier transform
DMA	direct memory access
ECG	electrocardiography
FET	flash emulation tool
FFD	full-function device
FFT	fast Fourier transform
FIR	finite impulse response
FN	false negative
FP	false positive
FRABOS	frame based operating system
FSR	force-sensing resistor
FPU	floating point unit
GTS	guaranteed time slots
GUI	graphical user interface
I2C	inter-integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IIR	infinite impulse response
iNODE	intelligent Network Operating DEvice
ISR	interrupt serve routine
JTAG	joint test action group
LR-WPAN	low rate wireless personal area network
MAC	media access control
MEMS	micro electro-mechanical system
MPDU	MAC protocol data unit
OP	operational amplifier
OSI	open systems interconnection

PAN	personal area network
PCB	printed circuit board
PD	Parkinson's Disease
PHY	physical layer
PPDU	PHY protocol data unit
PPV	positive predictive value
PTM	Pan-Tompkins method
RAM	random-access memory
RF	radio frequency
RFD	reduced-function device
RIP	respiratory inductive plethysmography
RISC	reduced instruction set computer
SD	secure digital
SPI	serial peripheral interface
TMM	template-matching method
TTL	transistor-transistor logic
TP	true positive
μC	micro-controller
UART	universal asynchronous receiver/transmitter
UPDRS	unified Parkinsons's Disease rating scale
USART	universal synchronous/ asynchronous receive/transmit
USB	universal serial bus
USS	ultra-small-stack