33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Low-Power Sensor Module for Long-Term Activity Monitoring

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***Abstract*— Wearable sensor modules are a promising approach to collecting data on functional motor activities, both for repeated and long-term assessments, as well as to investigate the transfer of therapy to activities of daily living at home, but have so far either had limited sensing capabilities, or were not laid out for long-term monitoring. This paper presents *ReSense*, a miniature sensor unit optimized for long-term monitoring of functional activity. Inertial MEMS sensors capture accelerations along six degrees of freedom and a barometric pressure sensor serves as a precise altimeter. Data is written to an integrated memory card. The realized module measures ⌀25×10 mm, weighs 10 g and can record continuously for 27 h at 25 Hz and over 22 h at 100 Hz. The integrated power-management system detects inactivity and extends the operating time by about a factor of two, as shown by initial 24 h recordings on five energetic healthy adults. The integrated barometric pressure sensor allowed to identify activities incorporating a change in altitude, such as going up/down stairs or riding an elevator. By taking into account data from the inertial sensors during the altitude changes, it becomes possible to distinguish between these two activities.**

I. INTRODUCTION

Asessments of motor function are crucial to identify appropriate therapies for patients suffering from neurological injuries such as stroke and adapt these therapies to the patient's individual progress. Clinical scales such as the Fugl-Meyer Assessment (FMA) or the Wolf Motor Function Test (WMFT) are used to assess the extent of sensorimotor impairment as well as to monitor the recovery over time. These tests are typically performed by physicians, physical or occupational therapist in a clinical environment at discrete time points. These assessments provide useful information on the efficiency of therapy in rehabilitation centers and help determine when a patient can return home. Unfortunately, such assessments are often time-consuming to administer and provide subjective data that is difficult to compare.

An important aim of therapy is to restore a certain level of independence in daily tasks. However, only little and mostly subjective information about the patient's behavior at home, in his familiar environment, is available. The transfer of therapy to activities of daily living (ADL) and the evolution of motor recovery with respect to daily activities remain largely unknown.

Wearable sensor modules that can be worn over extended periods of time and then sent back for data analysis, similar to a Holter monitor (e.g. for electrocardiography), are a promising technology to gather such data. Actimeters, the currently most widely available technology, are electronic devices that are typically worn on the wrist or ankle to record activity levels over a time-span of up to several weeks on a single battery charge. Such devices store rectified and integrated acceleration values for specified epochs or the number of crossings of a predefined threshold in a specified epoch. These tools have successfully been used to investigate correlations between therapeutic outcomes and the amount of activity at home [1][2]. Actimeters, however, do not store raw acceleration measurements. This excludes them from being used to extract characteristics of motor patterns that are present in persons after neurological injury. The ability to characterize these motor patterns during daily tasks could improve the outcome of this kind of assessment. In [3] it was shown that raw acceleration data can be used for the assessment of motor function. In the study a set of upper limb mounted accelerometers were used to provide estimates of the Functional Ability Scale.

Fig. 1. *ReSense* sensor module in a rapid prototyped housing. Thanks to the small form factor it can easily be worn like a watch. The weight of this configuration is 21 g.

More advanced sensor technology combining accelerometers with gyroscopes and magnetometers can be used to precisely detect orientation of body parts and thus estimate posture during rest and activities [4][5]. Besides general activity monitoring, this type of motion sensor is widely used in the field of gait analysis as movements can be reconstructed from the sensor measurements [6][7]. A selection of small, portable devices combining such sensors for motion analysis applications are ETHOS [8], SHIMMER [9] and TEMPO [10]. All these modules incorporate radio communication for real-time data streaming. ETHOS and SHIMMER also feature a microSD card-slot for onboard long-term data storage. Battery capacity, however, limits the ability of the devices to record daily activities over long periods; the presented configurations last for less than half a

This work was supported by a private foundation. Roger Gassert is supported by the NCCR Neural Plasticity and Repair of the Swiss National Science Foundation.

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978-1-4244-4122-8/11/$26.00 ©2011 IEEE

day.

In this paper we present *ReSense* a low-power, watch-size sensor module incorporating inertial and pressure sensors to record precise posture and motion data for time spans that are unreached by other systems with a comparable form-factor. The module takes advantage of recent off-the-shelf three-axis MEMS gyroscopes that favor miniaturization and reduce the power consumption. With this technology, activities can be detected and, thanks to the precise sensor measurements, analyzed to extract movement patterns and potentially achieve objective assessments.

II. REQUIREMENTS

The development of *ReSense* was motivated by the potential of recording functional movements in a clinical or home setting over extended periods of time, i.e. for more than one daily cycle. The system should be small, light-weight, easy to don/doff, simple in use and robust. It should be able to identify meaningful movements and activities, such as arm reaching, pronosupination of the forearm and arm swing during walking, as well as climbing and descending stairs or riding an elevator. *ReSense* should therefore be capable of reliably detecting changes in altitude with a precision of less than one meter. A precise onboard clock is required in order to tag events with a time stamp and to synchronize multiple sensor modules. Data should be continuously written to an on-board memory that can easily be read out, and the module should be able to determine the activity level online in order to record data only during active phases. While our main focus is on activities involving the upper limb, the system should also be applicable to the measurement of lower limb motion for gait analysis.

III. SYSTEM

ReSense consists of state-of-the art sensor technology integrated on a watch-size circular printed circuit board (PCB) (Fig. 2). It comprises a microcontroller, sensors, expandable memory, an external connector and integrated power supply. Sensing components include a 3D accelerometer to detect reaching movements and a 3D gyroscope to detect pronosupination movements or arm swing during walking. To allow the detection of stair walking and identification of the walking direction – a common problem in activity monitoring [11][12] – the module is equipped with a precise barometric pressure sensor. A general overview of the system components and their interaction is given in Fig. 3.

A. System Components

1) Microcontroller: The data processing, communication and power management is handled by a 16bit low-power microcontroller (PIC24FJ64GB004, Microchip Technology). It can perform a maximum of 16MIPS, has 64kB of flash program memory, 8kB of RAM that can be used for buffering datasets and supports a variety of power-saving features such as doze, idle and sleep modes as well as clock switching. In addition, it provides a real-time clock and calendar (RTCC) which continues to run when the CPU and the peripherals are shut down. This is used to tag the recorded samples with a time stamp.

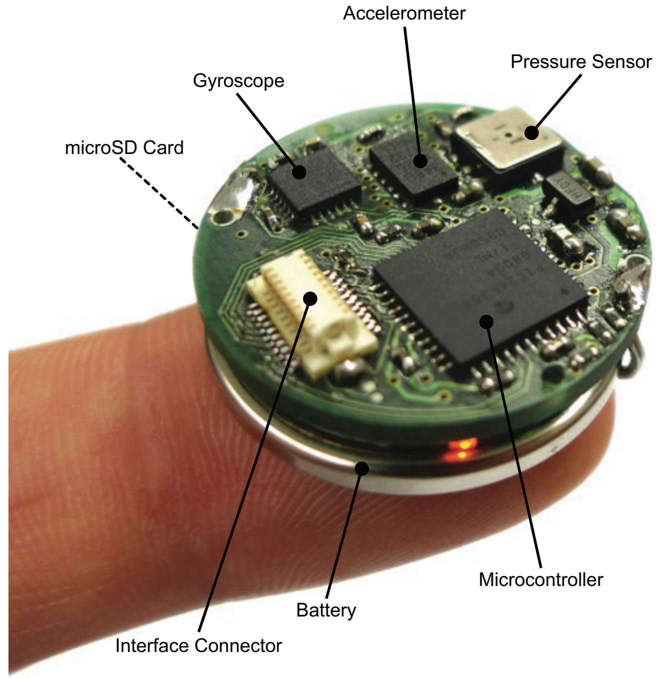

Fig. 2. *ReSense* module placed on the index finger. The module measures ⌀25×8 mm and weighs 8 g including a 100 mAh battery and microSD card (⌀25×10mm and 10 g in the case of a 200 mAh battery).

2) Sensors: Movements are monitored by means of a 3-axis accelerometer (ADXL345, Analog Devices) and a 3-axis gyroscope (ITG-3200, InvenSense). Moreover, a barometric pressure sensor (BMP085, BOSCH) meters the altitude with a theoretical resolution of 10 cm at sea level [13]. A compass was omitted as alignment with earth magnetic poles was not desired and as these devices are unreliable in indoor environments where *ReSense* will mainly be used.

All sensors perform the analog to digital conversion internally and are interfaced through an I2C bus. This increases the noise immunity of the system and lowers the power consumption of the processor.

3) Memory: Recorded datasets are stored on a 2GB microSD card mounted in an integrated card slot. At a sampling rate of 25 Hz, 8 16bit channels can be recorded continuously for more than 60 days, and cards with more memory are available.

4) Power: System power is provided by a rechargeable Li-Ion coin cell battery with a nominal voltage of 3.7 V and a capacity of 100 mAh or 200 mAh. Battery dimensions are ⌀24.5x3 mm or ⌀24.5x5 mm respectively. The analog and digital system voltage of 3.0 V is provided by low dropout regulators (LDO).

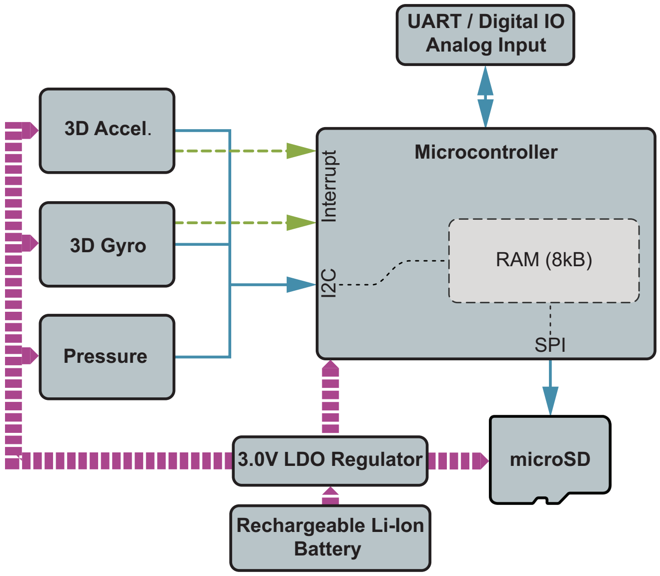

Fig. 3. System and power management block diagram. During phases of inactivity, the accelerometer switches to low-power mode and the other components are put to sleep. Upon activity, the accelerometer immediately sends an interrupt to the microcontroller, reactivating the other components.

5) Interface Connector: A 20-pin connector allows for the connection of external modules such as a Bluetooth communication interface for real-time data streaming. Also, nine pins, configurable as digital I/O or analog input, are available for expanding the capabilities of ReSense. The PIC microcontroller contains a high-speed USB Serial Interface Engine that can be used for fast and convenient memory readout.

B. Power Management

During the design phase a special emphasis was put on intelligent power management to keep the current consumption low and permit a so far unreached autonomy for this weight factor. Both accelerometer and gyroscope are equipped with a logic to sample data at predefined rates. Additionally, the accelerometer provides multiple, highly configurable interrupt sources; activity and inactivity detection being of special interest for this application. These interrupts can set the processor as well as all other peripherals into sleep mode in periods with no or low activity and wake them up once activity is present again. The pressure conversion is triggered by the microcontroller and the sensor goes to a low-power mode after the conversion is completed.

For very-long-term activity monitoring the power management can be divided into the following two states:

1) Activity State: When activity is present (detected by a change in acceleration of >125 mg along any axis compared to the first sample of a previous inactivity state), the system is put into a continuous sampling state and collects samples at a defined rate (25 Hz, 50 Hz, or 100 Hz). The microcontroller is in sleep mode and only wakes up to service the interrupt events triggered by the accelerometer or gyroscope when new samples are available. The sampled data is temporarily stored in an internal RAM buffer of 8kB size and, once this buffer is filled, the external microSD card is activated and the RAM buffer is written into the flash memory. After the procedure is completed, the microSD card is deactivated and the microcontroller goes to a low-power sleep mode and waits for the next sensor data interrupt.

2) Inactivity State: When the accelerometer detects no activity over a longer period (i.e. a change in acceleration of less than 125 mg along any axis over a 5 s period with respect to the first sample of this period), all components except the accelerometer go into sleep mode, resulting in a current consumption of less than 130 μA. The accelerometer continues to sample in order to detect if activity is present again, however, the measured values are not stored in memory. In case of detected activity, an interrupt wakes up the microcontroller and gyroscope and the sampling process continues. The maximum system wake-up delay can be approximated by the sum of the sampling interval of the accelerometer plus the wake-up time of 200 μs of the microcontroller. The gyroscope provides valid data 50 ms after initiation of the wake-up.

IV. CHARACTERIZATION AND EVALUATION

A. ReSense Module

The realized sensor PCB measures 25 mm in diameter and 5 mm in height, and weighs 3 g including all components. Using a rapid prototyping process we have designed a compact and shock-resistant housing that allows *ReSense* to be worn like a watch on the wrist or ankle (Fig. 1). The realized module is shown in Fig. 2.

B. Sensor Noise

Sensor noise limits the precision of the measurements. Noise in acceleration and angular rate was measured at a 50 Hz sampling rate in a static environment. The barometric pressure sensor was sampled at 5 Hz. Table I summarizes the noise levels for all three sensors. For the inertial sensors each axis is represented independently. The pressure sensor also provides temperature data as the pressure needs to be compensated externally. The noise level of compensated temperature, compensated air pressure and resulting altitude at 460 m above sea level are presented in the lower part of Table I. The relation between altitude and air pressure is described via the barometric equation [13]:

$$Altitude = 44330 \cdot \left(1 - \left(\frac{P}{p_0}\right)^{\frac{1}{5.255}}\right) [m] \qquad (1)$$

where $p_0 = 1013.25hPa$ is the mean pressure at sea level.

The results show that the noise in the pressure sensor is well below the required level of 1 m. Accelerometer and gyroscope noise levels coincide with the expected values from their respective datasheets.

TABLE I

RMS NOISE LEVEL OF ACCELEROMETER, GYROSCOPE AND PRESSURE SENSOR

	x-axis	**y-axis**	**z-axis**
Accelerometer $[mg]$	5.69	6.87	11.33
Gyroscope [°/s]	0.06	0.06	0.06

	Pressure	**Temperature**	**Altitude**
Pressure Sensor	0.06 hPa	0.02 $^\circ$ C	0.51 m

C. Gyroscope Zero Offset Drift

MEMS gyroscopes are known to have a zero offset in their output values which drifts over time in function of temperature. The ITG-3200 contains a thermometer to automatically correct for this drift and control the zero offset. In our measurements the maximum drift rate was less than $0.04^\circ/min$. This allows for integration of the rate signal during limited time windows without accumulating drastic errors.

D. Power Consumption

The current consumption of each single component at acquisition rates of 25 Hz, 50 Hz and 100 Hz (2.5 Hz, 5 Hz and 10 Hz for the pressure sensor) was measured to elaborate an estimate of battery runtime in function of sampling rate. The results are shown in Table II. To validate these estimates, the sensor module was programmed for continuous sampling at 25 Hz and powered by a fully charged 200 mAh battery with a voltage of 4.17 V. After 28 h the battery voltage reached 3.1 V; the minimum for proper system operation. The gyroscope consumes over 10 times more current than the rest of the system. Table II also includes estimates for a runtime when the gyroscope is completely shut down.

E. Initial Activity Recordings

Activity recordings were collected from five young, energetic subjects (four male, one female, all right-handed) over a period of 24 h (Fig. 4). Subjects wore a *ReSense* module on the wrist using a wristband, which was removed only for showering as the prototype case was not completely waterproof. The recordings allow to identify the ratio between activity and inactivity state of *ReSense*. This ratio gives an idea of the total time span the sensors can record ADL. The outcomes showed that during about 50% of a daily cycle the system samples data and is in rest mode the rest of the time.

TABLE II

POWER CONSUMPTION IN FUNCTION OF SAMPLING RATE (CONTINUOUS SAMPLING)

Sampling rate	**25** Hz	**50** Hz	**100** Hz
Active mode current $[mA]$	7.4	7.8	8.8
Sleep mode current $[mA]$		0.13	
Runtime @ 200 mAh $[h]$	27.0*	25.6*	22.7*
Runtime @ 200 mAh, gyros off $[h]$	500*	290*	138*

* Estimates based on active mode current measurements.

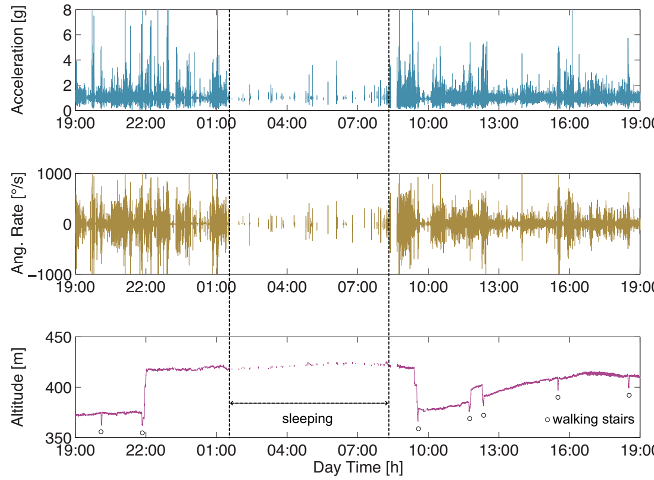

Fig. 4. A representative 24 h recording showing the activity of the right lower arm for a 30 year old healthy female subject. Shown are the norm of the acceleration (top), the angular rate of pro-/supination movement (middle) and the altitude profile (bottom). During the sleep period of the subject, the system was mainly shut down and in low-power mode. Overall, the module was active during about 54% of the time. Changes in altitude correspond mostly to stair climbing as shown by peaks in the inertial measurements. Changing weather conditions caused a slow drift in the altitude profile after 10 a.m.

A second measurement was carried out to demonstrate the performance of the barometric pressure sensor. A healthy subject wearing a *ReSense* on the right wrist walked up a staircase of 9 m height and subsequently took the elevator. The corresponding data is shown in Fig. 5. It can be seen that the elevator rises faster and is characterized by less arm movement.

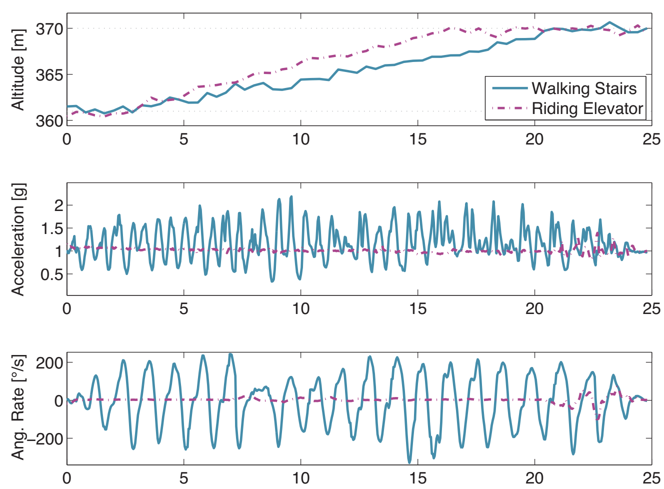

Fig. 5. Comparison of walking stairs with riding an elevator. The sensor module was worn on the right wrist while a subject climbed a staircase with a height of 9 m and subsequently took the elevator for the same height. The plots show the altitude profiles measured with the pressure sensor (top), norm of the accelerations (middle) and the angular rate of the arm swing movement (rotation around the axis perpendicular to the dorsal aspect of the wrist) (bottom).

V. CONCLUSIONS

This paper presented a miniature sensor module for precise long-term monitoring of human motor activities. Thanks to the small size and light weight, *ReSense* can easily be worn on the wrist and ankle without disturbing natural movements.

The combination of state-of-the-art low-power components, advanced power management and large amount of memory allow to extend the continuous recording time up to 27 h at a sampling rate that is sufficient to capture most activities of daily living. Initial tests on five healthy subjects showed that *ReSense* needs to be active only about 50% of a daily cycle resulting in an almost doubled battery runtime. It can be hypothesized that the ratio of activity/non-activity of patients with disabilities will be even lower and that the battery runtime will therefore be further extended. Another factor to improve power efficiency is to determine ideal activity and inactivity thresholds as well as the time it takes until inactivity is declared. For this purpose additional tests have to be performed.

The runtime of the module is determined mostly by the gyroscopes, which consume about 10 times more power than the rest of the components. A more sophisticated approach to increasing battery runtime will therefore be to enable gyroscope operation only at pre-defined day times or when the accelerometer pre-classifies specific activities which should be captured in detail – this is realistic as the processor can perform approximately 500 times the amount of operations currently required. Finally, the continuous improvement of sensor and battery technology will positively affect the long-term operation of the module.

The integrated barometric pressure sensor showed to be a promising means of detecting activities such as walking stairs and distinguishing ascent and descent or the use of an elevator. Typical pressure patterns can provide additional information about activities of daily living.

Future work will focus on the extraction of movement features and characterizing movements corresponding to ADL. The system also has to be validated in a clinical setting with patients.

VI. ACKNOWLEDGMENTS

We thank Andreas Luft and Roman Gonzenbach for the fruitful discussions, the subjects who participated in the 24 hour recordings, and Olivier Lambercy for his helpful comments on the manuscript.

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