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ScienceDirect

Procedia Engineering 147 (2016) 671 – 676

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

Wearable, modular and intelligent sensor laboratory

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Abstract

In this paper, a modular sensor system for recording pressure distribution, 3D-acceleration, 3D-angular velocity, temperature and humidity in a shoe insole is presented. The intelligent sensor-insole is a measurement system that can be used in medical and sport related fields. Integrated sensors record physical parameters such as acceleration and or pressure which can also be used to trigger an additional feedback system. Through intelligent and high performant electronics, the feedback system is able to operate in real time. The combination of individually miniaturized systems, wireless data transmissions and a rechargeable battery enables the system for a wide field of application such as fall prevention, training analysis and motion optimization. Robust and miniaturized hardware components as well as wireless communication technology enable real-time processing of data. Measurement data can be stored locally on the measurement device for post analysis, as well as visualized on connected mobile devices such as smartphones or tablets. Aiming at using the system as a mobile and easy-to-use lab, both under laboratory conditions and in field. Applications like gait- and running analysis outside the laboratory, fall detection and activity monitoring in a home environment are possible. Due to the high performance of the system, the data pre-processing can be performed on the embedded system. Because the system supports wireless connections, it is possible to combine several of the systems to build a sensor network. Furthermore, it is possible to transmit the collected data to a cloud. The system will provide the measured data in different levels of complexity. For instance, the system is able to evaluate the data automatically and provide the results to experts such as physicians and coaches.

Peer-review under responsibility of the organizing committee of ISEA 2016
Keywords: Instrumented insole; sensor network; wearables; data fusion; feedback system; realtime anaylysis

1. Introduction

Human movement in general and locomotion in detail is a fascinating filed of science and research. The amazing functionalities and adjustments of the various physical components and signal processing have always moved scientists in the broadest meaning of the word. The will to understand the complex processes during human movement led to strong efforts towards the development of increasingly sophisticated measurement technologies for monitoring not only the human motion itself, but also the interaction to the environment and pieces of sports equipment, medical devices or technical systems of any kind. Most measurement systems serving for the purposes described are laboratory bound, i.e. they are intended to be used inside a closed, finite space. That gives great advantage in regards of high consistency of boundary conditions, low impact of environmental influences like temperature, humidity, wind etc. and good synchronization of different systems due to permanent installation of the measurement equipment. The downside of laboratory based measurement systems if of course the more or less artificial scenery. The closed, finite space influences subjects' perception, possibly followed by a change of movement patterns. This is potentially true especially for highly dynamic movements. Also the measurement time is limited due to the fact, that distances of motion are strongly limited. This yields the necessity to whether cut the motion into small portions (walk or run for several meters) or convert long-distance motions to stationary ones (running is performed on treadmills, cycling on ergometers

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1877-7058
Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.270

etc.). Both approaches clearly alter the human movement patterns by either adding kinetic components (accelerating/deceleration during within few steps for in-lab running) or removing them (no horizontal acceleration of the body's center of mass for treadmill running). Studies based on laboratory measurements revealed many valuable information for a growing understanding of human movement, motion and interaction with technical structures.

Nevertheless lately there is an increasing interest to overcome in-lab limitations. First motivation for this tendency are studies that have clearly shown the limitation of laboratory studies in regard of getting near to "real values" [1]. In a general sense, enhanced field-testing could answer the question, if results of in-lab measurements are in parallel with ones derived from field measurements in order to validate lab testing procedures. But moving from lab- to field-testing requires totally new qualities for the measurement equipment in terms of portability (size, weight, power supply etc.) while maintaining performance (sampling rates, resolution, synchronisation, etc.)

2. State of the Art

Miniaturized measurement technology increasingly supports researchers at measuring tasks as well as studies of movements and forces in sports and medicine. Commercially available measurement systems and sensor platforms are able to decrease length and effort of development time and allows to focus on the analyses of study results. The usage of wearable inertial motion sensors allows to perform motion and gait analysis outside the laboratory [2]. For mobile applications two major groups of measurement equipment are available, namely inertial sensor systems and measurement insoles.

2.1. *Inertial Sensor Systems*

Existing systems like the Xsens MVN BIOMECH system (Xsens Technologies BV, Netherlands) are used in science for biomechanical studies and analyses, sports performance science or rehabilitation. Up to 17 wireless inertial measurement units (IMU) can be used to transmit the data to the receiver. Software with biomechanical models and sensor fusion algorithms create real-time 3D animations or perform calculations of e.g. joint angles. The wireless body sensor technology of Shimmer (Shimmer, Ireland) provides more flexibility to enable for a wider field of application. Besides kinematic data it can also collect biophysical data such as ECG, EMG and heart rate, when extended with sensor modules. Overall, up to 60 sensors can be used simultaneously to collect data. With this flexibility, measurement systems can be configured and customized individually. The introduced motion trackers have to be attached to the patients shoe or ankle joint to enable gait analysis.

2.2. *Measurement Insoles*

Instrumented insole systems offer a variety of degree of integration of sensors and computing technology as well as energy supply and hereby offer a very wide field of application. However, at the current state, most instrumented insoles require at least one component to be externally attached to the shoe or ankle joint. Integrated force/ pressure sensors are used to record pressure values and distributions under the sole. Further parameters such as center of pressure may be derived from it. Furthermore gait events, e.g. heel strike, temporal spatial parameters, e.g. cadence, or ground reaction forces can be calculated.

The Pedoped insole (novel GmbH, Germany) is a load monitoring device with one large force sensor that measures the normal plantar force. A small unit contains all required electronics and enables wireless communication with a smartphone to display the calculated data, which means that it can also be used as a feedback system. Further on, the Pedoped insole can be used as a long-term monitoring system for walking or running and provides data about user’s stability and balance. The pressure measurement insole SurroSense (ORPYX Medical Technologies Inc, Canada), that also requires an externally attached unit, analyzes the pressure conditions below the sole by means of eight sensors. Live-feedback can be displayed on a smartwatch and provides current values and warnings when reaching certain thresholds. The purpose of the system is to help patients that suffer from sensory loss under the foot due to diabetes and also those who have a high risk of foot ulcers. Thirteen capacitive pressure sensors and one 3D accelerometer are the main features of the OpenGO sensor insole (Moticon GmbH, Germany) that measures pressure distribution, center of pressure, total force and acceleration. The kinetic data as well as gait parameters are used for training monitoring and movement optimization supporting athletes and patients in rehab. The system was successfully used to measure gait differences during aftercare of lower extremity fractures [3]. The measurement results can be evaluated on any computer or mobile device through a software interface. Even though it is possible to synchronize the insole with further measurement technology (EMG), it cannot be expanded with additional units. On the other hand, all electronics are fully integrated into the insole. Further insole systems are RPM2 (Remote Performance Measurement, USA), Tune (Kinematix, Portugal), and GaitShoe (Veristride, USA). The WALKiNSENSE by Kinematix (previously Tomorrow Options, Portugal) is the only system commercially available that allows an individual positioning of up to eight sensors that also includes a 3D accelerometer and 3D gyroscope. Beside validation and reliability studies [4, 5, 6], the system was primarily used for medically motivated studies [7, 8, 9]. Besides the feedback on a smartphone or computer screen, actuator elements can be directly integrated into the sole and serve as guidance for blind people by providing direct stimulation to the foot and simplify walking navigation [10]. Watanabe et al. [11] provide a guidance method to regulate a person’s walking pace. Additional pressure sensors in a sandal can serve as a step detector. This also suggests the application in training for sports and rehabilitation. The development, however, is tied to a specific shoe and cannot be used flexibly in everyday life. Also similar to a sandal and with an additional belt unit is the solesound [12] that provides audio tactile feedback in real-time for Parkinson patients. Kinematic and pressure signals are provided by four pressure sensors and an IMU, while feedback is given by five actuators in the sole. Due to its wireless capabilities and full integration, the sole of operated with piezoelectric actuators (Wyss Institute, USA [13]) differs from previous systems [14, 15] and is suitable for everyday life.

2.3. Summary

In conclusion, inertial sensor platforms are available. that offer modularity and are usable for different measuring tasks in sports and medicine. Recent measurement and feedback insoles are not designed to be modular or expandable for additional sensor applications. Moreover, there are only few systems ready to use in everyday life.

This led to the request, to design a sensor platform, which does not only combine known features but also offer enough flexibility to be adapted to a wide variety of applications. The focus of the project described in this this paper should lead to a wearable, modular and intelligent sensor laboratory.

3. System Overview

The main target of the system design was to develop a flexible system for measurement and feedback that offers a high level of modularity. This should be facilitated through seamless integration of different types of sensors, ability to regulate attached actuators and interconnectivity between devices for simple expandability to a sensor and actuator network.

3.1. System Requirements

The new measurement system is to be designed as wearable, modular and intelligent. The attribute *wearable* incorporates requirements as small dimensions, light weight and robustness against environmental influences like temperatures, humidity, impact shocks etc. The *modularity* of a measurement system should be proven by allowing to effortless attach sensors of different physical effects and ranges, by being able to regulate or control different actor devices whether tactile, optical or wireless attached. The attribute *intelligent* of course is the most hard to earn. In technical terms intelligence means to be able to autonomously optimize processes or being able to process natural phenomena like speech or pictures. In case of a data acquisition device, it should be able to adapt to different sensors, voltage-ranges of the sensor and presence of additional devices without user intervention. For a feedback device, some abilities to adapt the actoric signal to changing environmental or sensing conditions will be required.

3.2. System design

The system is designed from a framework approach, consisting if three parts: (i) at least one measurement system (node), (ii) the data analysis, and (iii) the data visualization (Fig. 1).

(ia) Measurement System: To fulfil the requirements concerning dimension and wearability a System on Chip (SoC) is used that is highly integrated. The SoC provides a high performant dual-core CPU, integrated fast memory, wireless interfaces such as WiFi and Bluetooth, and wired interfaces such as I2C, USB and SPI that make the system modular and flexible. The sensor attachment to the SoC is realized by an additional printed circuit board (PCB). The PCB provides all required interfaces to connect different sensors like 3D gyroscope, 3D accelerometer, temperature and humidity sensor, strain gauges and pressure sensors, whether as single sensors or as a sensor array like an external pressure distribution insole. Furthermore, six high precision AD-channels are available to extend the sensor system. The pressure sensor array for use as insole consists of eight single pressure sensors that are placed under specific areas of the foot. Data storage is possible on the system, on a connected mobile phone and through that on a remote server or cloud storage.

(ib) Wireless measurement system network: One measurement system can work as a standalone device. For applications where more than one sensor system is needed additional measurement systems can be added using an ad-hoc connection technology. Due to the usage of a robust communication standard, a high data transfer rate and transmission range is ensured. The measurement system provides a server-client based communication. The measured data can also be buffered or stored on each measurement device if the connection is lost or no live stream is required. Time synchronisation is very important to get all measurement values of each device in the equal timeline. Since each device is connected to each other this can be done easily.

(ii) Data analysis: Because of the high performant SoC, which is used in each device, a high level of pre-processing can be implemented. The pre-processing functions include functionalities such as filters (i.e. fast fourier-transformation (FFT) for frequency analysis or high-/low-pass filter) or event recognition. The implemented software is able to extract meta-data to simplify the post processing and data presentation which can be done in a cloud server or on the users end device. That means, that data output from the measurement system is scalable from the complete raw data stream to a down sampled and pre-processed data stream to just sending status information when required. The streamed data is stored in a database which is accessible either from the sensor network or from the users' devices such as PC, tablet or smartphone. The application specific data fusion and evaluation of the measurement data can be done by the cloud server, the sensor network in real time or manually.

(iii) Data visualisation and feedback: The visualisation takes place on three levels of abstraction. The low-level of abstraction is just providing the raw or meta-data by a database application programming interface (API). With this functionality is easily possible to implement additional analysis software tools or process the data in simulation environments such as Matlab. The results of the simulation and the data fusion provide the basis to develop algorithms for the second level of abstraction. With this second level an advanced graphical user interface (GUI) is available. Based on the pre- and post-processing and data-fusion algorithms application specific visualizations is implemented. These parameters can be used by specialists, i.e. physicians in the medical or coaches in the sport field, to give recommendations. The high level of abstraction is the end users interface which is a specific kind of feedback system. In the simplest case this is merely a blinking LED or vibration actuator in the insole. Nevertheless, it is also possible to implement a mobile application that gives recommendations automatically, provides additional information and gives the opportunity to share the information with medical staff, trainers or other people via social networks.

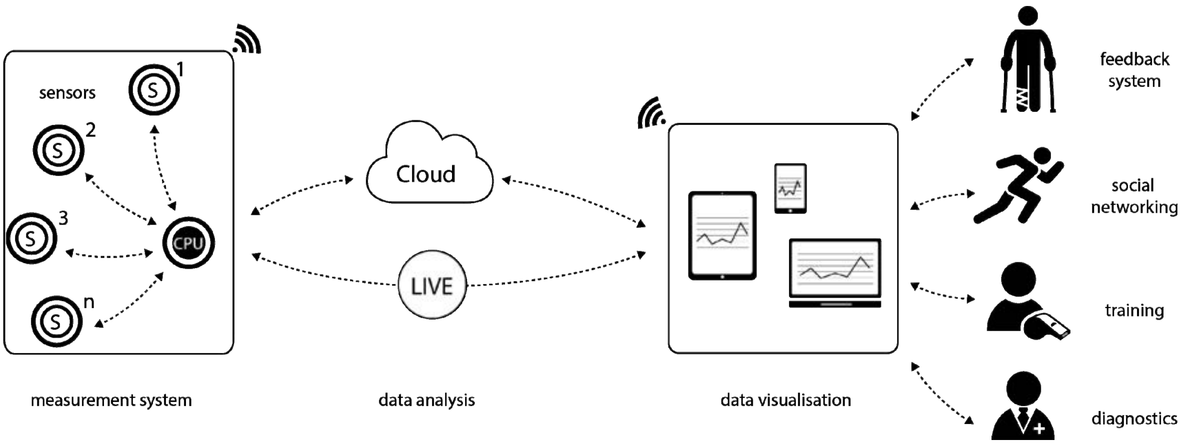

Fig. 1. Measurement system – communication and data flow.

3.3. System implementation

The system consists of (i) two hardware parts, i.e. measurements system and Sensors, like a pressure measurement insole, and (ii) three software parts, i.e. (a) embedded software, (b) cloud processing system and (c) configuration and application software for PC/mobile devices. Through the whole implementation process the hard- and software have been designed to comply with all system requirements.

(i) Hardware: The first part of the hardware, i.e. the measurement system, contains the SoC PCB with a socket expander for attaching a custom PCB (Fig 2b). As mentioned in 1.2. a high performant processing and communication unit is used. Therefore, the Intel Edison platform (released in 2014) was chosen (Fig. 2d). Although the platform's size is that of a postage stamp, it provides a dual-core CPU, 1 GB RAM, 4 GB EMMC Memory and WiFi communication on-board with low power consumption. For the sensor data acquisition an additional four layer PCB with embedded sensors was designed. This board contains currently a 3-axis acceleration sensor with a range of ±16 g, a 3-axis gyroscope with a range ±2000 °/s, a high precision zooming analog-digital converter (ADC) with six single-ended or three differential channels with a resolution of 16 bit. Furthermore, the SoC extension provides a multiplexing system for attaching a multichannel pressure sensing insole, a temperature sensor and a driver unit for a vibration element in the insole.

To make the system mobile and wearable a 600 mAh Lithium battery (Fig. 2c) is used. Using the complete performance of the processor results in reduced operating times of about four hours, which is still appropriate for single training sessions. If the full computing performace or continous Data streaming is not required, measuremt time extends significantly

The System can be charged and connected to a PC with a USB interface. The entire measurement system including housing weights 30 g and has the dimension of 27 x 45 x 20 mm (Fig. 2a). The Second part of the hardware currently consists of an insole. It contains an 8-channel resistive pressure sensor (IEE High Dynamic Force Sensing Resistor) [16]. Each cell covers a range of 0.1 bar to 7.0 bar and has been calibrated individually. Additionally, a vibration element was placed in the front part of the insole to act as a feedback system. The insole consists of three layers. The lowest layer is made of a strong synthetic material which is individually adapted to the foot. In this layer, a piezoelectric actuator is also integrated. On top of that layer the sensors are located. The final layer is covering the sensors (Fig. 2f). All layers are bonded together. The insole can be connected to the measurement system by means of a flat ribbon cable so that it can be changed easily (Fig. 2e).

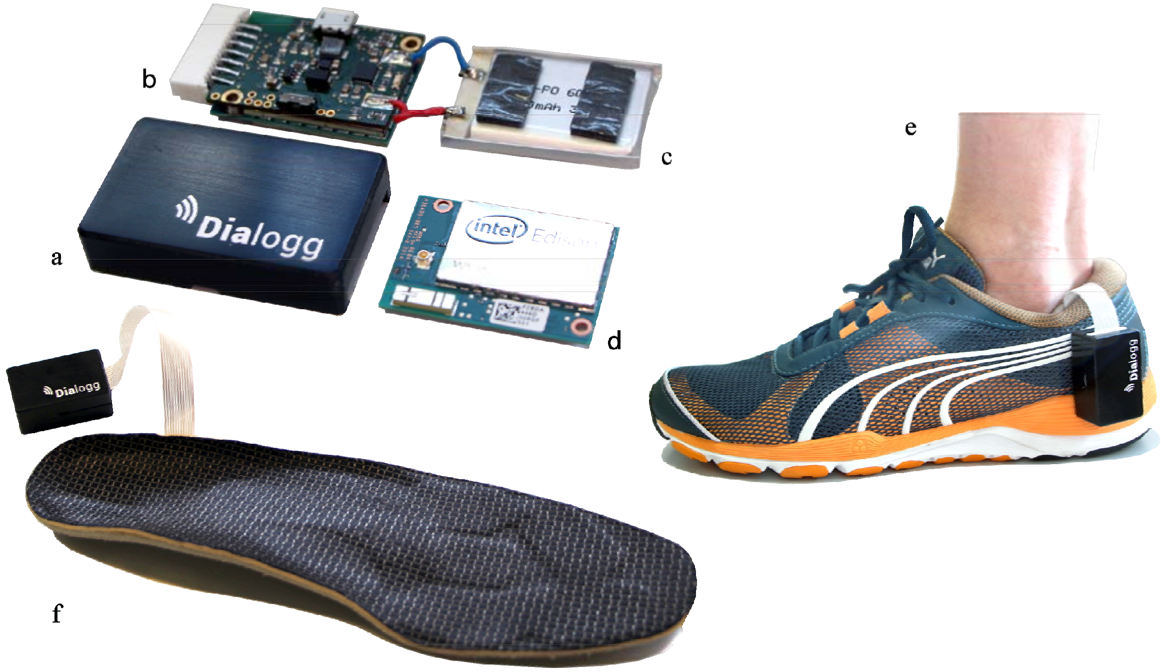

Fig. 2. (a) housing; (b) custom sensor PCB with sole connector; (c) battery; (d) Intel Edison SoC; (e) running shoe with insole and measurement system; (f) insole connected to measurement system.

(ii) Software: (a) the embedded device (Intel Edison) runs a real-time linux operating system. This allows a modular design to extend the measurement framework easily. The software can be written in C++ and consists basically of four parts: communication, device driver, memory and data pre-processing. One measurement system (node) is acting as a router. On the router/master node a TCP/IP-Server is running. If more than one sensor is used, all other measurement systems are clients and transmit their data to the server. The embedded software manages the connections between the measurement devices and external devices such as PCs or mobile devices that collect data and provide functionality of device configuration through WiFi. Furthermore, the embedded system manages the data collection. The implemented drivers for the sensors integrated circuits (ICs) provide data capture functions. Each sensor is controlled by a separate thread, which is buffering measurement data and makes it available on demand. The measurement devices provide a maximum sampling frequency of 1 kHz for each sensor. A further task of the embedded software is the pre-processing, which contains filter functions, compressing functions, e.g. zip, and meta-data generation. The pre-processing can also be extended by application-specific tasks, calculations and data-fusion algorithms. All measurement data can also be stored on the measurement device locally in a compressed database.

(b) The Cloud processing software is – like the embedded software – hidden from the user. It is also written in C++. The software runs on a server PC. All captured data can be stored on the cloud server that is connected to the internet. All devices that are connected to this server can read and process the measurement data. This allows a remote access to the sensor-network.

(c) The configuration and application software is running on the user's smartphone, tablet or PC. It provides two main-features – communication and visualisation. The user can access the cloud-server, its database and post-processing services as well as access the measurement system directly by using a live stream. It is also possible to setup the measurement system i.e. adjust sampling rate or enable/disable sensors separately. The application software is written in .NET C# for PC and JAVA for the mobile devices.

4. Discussion

The system developed exhibits low weight and small geometric dimensons. A battery life of at least 4 hours is sufficient and can be extended by downscaling the performance (e.g. volume of data streamed) to a full day of activities. Hereby the postulated *wearability* is achieved.

The system combines the advantages (e.g. flexibility and connectivity) of sensor platforms with instrumented insole-applications and solutions (data-processing and deduction of meta-data). Beyond that it provides a powerful, scalable and programmable processing unit and the option of implementing actuators or display options according to the requirements mentioned in 2.1. It is able to measure simultaneously different kinematic and kinetic parameters Further scalablility is achieved by the option of building a wireless network to monitor multiple sensor-nodes simultaneously. The high demands in terms of computing power for pre-processing are met by the chosen SoC. Due to the cloud-connectivity the measurement data is available at any time from any device. This is useful for training monitoring and control in sports and patient monitoring in medical applications. Last the operation time can be influenced by scaling either the computing performance or the battery capacity. The high level of flexibility in many aspect makes the system *modular*.

The flexibility of the systems in terms of self-organzied multi-node networks was successfully implemented, the zooming ADC adapts to the signal range to constantly achieve the highest possible conversion precision. The system detects possible options for data storage (onboard, connected mobile device, cloud storage) and choses the appropriate destination in respect of availability. The automatic adaptation options could be considered *intelligent* in respect of the use in technical environments.

The implemented combination of properties and capabilities meets the requirements of many settings for in-lab use. The portability of the system brings state of the art data aquisition abilities to real-live applications. This enables a new dimension in field testing, being expressed by the term outdoor *laboratory*.

5. Conclusion

The wearable, modular and intelligent sensor laboratory presented has been successfully implemented. The use of a robust industrial wireless standard in combination with sensor network technologies and sensor data fusion offers the possibility to collect data of multiple objects and devices in a wide area. Simultaneously a cloud system can provide services that all measurement data can be retrieved at any time from any device. Additionally through real time operation and live streaming a feedback system is possible. Various applications in sports and medicine will be deepened in further studies.

Acknowledgements

Europäische Union
Europa fördert Sachsen.
ESF
Europäischer Sozialfonds

This work was supported by the State of Saxony and the European Union (European Social Fund ESF).

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