# Scalable, Wearable, Unobtrusive Sensor Network for Multimodal Human Monitoring with Distributed Control

Marek Kulbacki[1], Roman Koteras[2], Agnieszka Szczęsna[2], Krzysztof Daniec[2], Robert Bieda[2], Janusz Słupik[2], Jakub Segen[1], Aleksander Nawrat[2], Andrzej Polański[2], Konrad Wojciechowski[1]

[1] Polish-Japanese Institute of Information Technology, Warsaw, Poland
[2]Institute of Informatics, Silesian University of Technology, Gliwice, Poland

*Abstract*— **We present the concept and implementation of unobtrusive wearable network of sensors and distributed control system for integrated monitoring - acquisition, processing, analysis of human motion and other physiological modalities. The entire system, hardware and software are scalable and compliant with the Wireless Body Area Network model. The wearable system modules can work independently and continuously indoor and outdoor. Each of the tracking and controlled subjects is wearing a Body Acquisition System (BAS). BAS is a human acquisition system for monitoring human motion and multiple physiological signals. It is built into a wearable unobtrusive smart clothing and enables to create wireless sensor network using WIFI for external communication, local hub for local data acquisition, processing and transfer. The central hub for global data processing and data exchange has been developed as Cloud Based Human Multimodal Database (CBHMD). A software application, Multimodal Data Environment (MMDE) has been built to visualize and control the acquisition and monitoring process. MMDE allows domain experts such as physicians, physiotherapists, film producers, to work with connected BASs control and react in real time. MMDE enables remote communication, data acquisition directly from BASs, diagnostics, management and maintenance of medical devices in BASs, as well as data processing using customized processes and algorithms.**

*Keywords*— **Wearable Systems, Motion Acquisition, Motion Control, Wireless Sensor Network.**

## I. INTRODUCTION

The technology for fast and simple transmission of information about vital parameters of geographically distributed subjects (patients, physicians) is desirable in telemedicine, e-health, sport, entertainment and other areas where one person needs track another person remotely. The reasons for remote measurements of subjects is to improve the general health, the quality of life or to limit the overall healthcare costs. Remote monitoring allows to test and use new science achievements in real life scenarios. An example of a function of biosensors and the cooperating software is registering and transmitting selected life parameters of the patients in ambulatory conditions, which will allow the supervising staff, equipped in appropriate diagnostic apparatus, to evaluate the occurrence of undesirable conditions.

One of the main technical aims is to develop a multifunctional, intelligent, wearable mobile system compliant with Wireless Body Area Network standard [1][2]. Such system could be targeted to telemetry, rehabilitation, remote monitoring, acquisition and control. The existing systems are not able to work effectively for a long period of time because of high power consumption. A detailed overview of the different variants of communication standards for the purpose of telemedicine with drawing the attention on power consumption problem is presented in [3]. Currently available wireless systems require special installation and calibrations of the whole system, frequently using invasive measurement technologies or large sensors. We have developed wearable system for full body motion tracking as well as lightweight, unobtrusive IMU sensors with low power consumption significantly smaller than currently available on the market solutions (Fig.1).

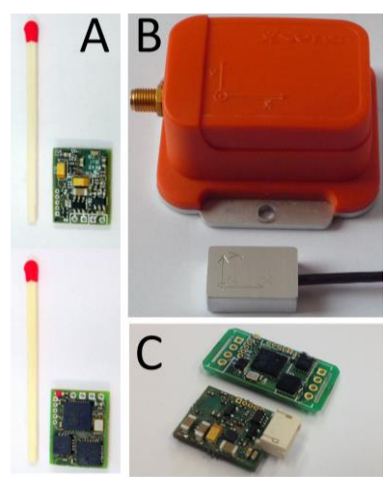


Fig. 1 Wearable IMU sensors comparison
A) I-st version of our IMU sensor; B) comparison I-st version of IMU (silver box) with Xsens IMU solution (orange box) C) 2-nd version of IMU (slim and longer) with 1-st version

The main problems of the current mobile monitoring and telemetry technology include data transmission, security of the measurement data, energy requirement [4][5], and interoperability. While there are market and research [6] solutions capable to work in paired configurations: one wearable clothing and one client application, but without the possibility of multiplying the wearable system (where one system controls many suits) or of computer software (where data from one suit is broadcasted within many client applications).

During the last few years we have successfully created and deployed hardware and software elements of IT solution that enables secure distributed measurements of human body parameters, is able to work long period of time and is scalable. The software elements contains Cloud Based Human Multimodal Database and Multimodal Data Environment. The hardware parts are Body Acquisition Systems - unobtrusive, wearable smart clothing in a form of customizable wireless sensor network nodes (Fig.2).

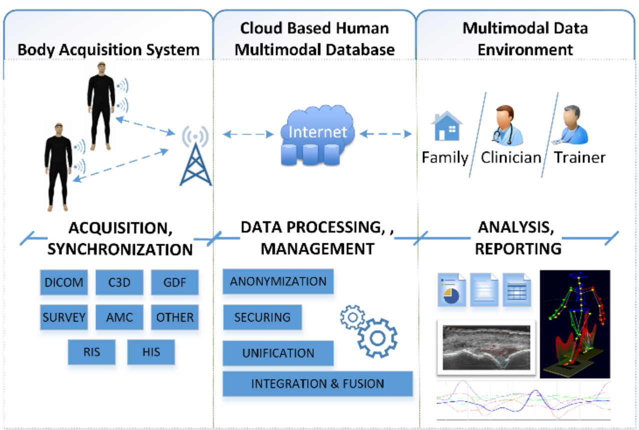


Fig. 2 Elements of Multimodal Data Environment

## II. MULTIMODAL DATA ENVIRONMENT

To fill in the gaps among tools and methods for human motion acquisition, processing, analysis and synthesis, research and development have been undertaken at Polish-Japanese Institute of Information Technology in Bytom, Poland. We have developed algorithms for low level processing of motion data, decomposable and personal muscosceletal models applicable to medicine, the advanced motion database enabling to store processed and indexed data, together with the tools allowing the numerical analysis. The conducted research include development of methods, accepted by medical environment, for creation of low-dimensional representation of motion enabling perceptive comparison of movements, classification and motion visualization. If necessary one has to translate data into meaningful information and deliver it in a timely and acceptable manner to relevant stakeholders. The achieved results include technological elements: Body Acquisition System (BAS), Cloud Based Human Multimodal Database (CBHMD) with web services for data processing and unified 4GAIT-HM, 4GAIT-Parkinson and 4GAIT-MIS datasets [7] and Multimodal Data Environment constituting the grounds for development of the existing and creation of the new advanced products and services in the area of motion analysis and synthesis.

The Cloud Based Human Multimodal Database is the successor of Human Motion Database [8] developed at PJWSTK in 2010. It is more general than its predecessor and depends on conventional technological solutions involving common protocols and data formats used by a stateless, service oriented interface layer. It enables for integration with various client platforms while maintaining a uniform mechanism for user identification and authorization. Although the primary role of this component is providing the repository functionality for publishing, updating, browsing and retrieving of multimodal time series data, the system also allows to create workflows for data processing and provides management functionalities for that. Simple data processing and workflow management are interrelated, since even the simplest data access scenario requires determining the user role and their privileges, resource being in an appropriate state of its lifecycle, and, from the other side, some use cases of the existing resources cause the update of the persistent data. Two conceptual layers of the database system's functionality can be distinguished: one containing data collection, unification, storage and retrieval, the other online collaboration over the stored data.

Motion Data Editor [9] was originally designed to support physicians in viewing medical data for diagnosis of various human movement disorders. It has been reorganized and refactored to become a general purpose data processing software, Multimodal Data Environment. It enables simultaneous communications with any number of Cloud Based Human Multimodal Databases using web services or direct communication with any number of Body Acquisition Systems directly or in remote locations. It supports processing multimodal data from any number of measurements simultaneously and synchronously, and offers an automation report generation not only for one trial but also for the long-term data analysis. It reduces the time for data analysis significantly and puts the focus on data interpretation instead of calculation. It works with a few dozen industrial measured data formats, which facilitates the processing and analysis of multimodal kinetic, kinematic, ground reaction forces and currently also electromyography data as well as fusion of ultrasound and Power Doppler data. The application architecture uses data sources, processing and terminating elements and allows one to create any number of information flow graphs and enables flexible system development by composing information flow graph from flexible processing elements. It allows users to dynamically create new data flows without any knowledge of programming. Visual Data Flow (VDF) environment supports user in creating data flows by presenting graphically available nodes. It guides the users, by showing them how particular nodes can be connected, according to basic model rules and data types compatibility, to infer new data from existing measurements.

## III. BODY ACQUISITION SYSTEM

The second developed part is Body Acquisition System – wearable platform intended for data acquisition and control

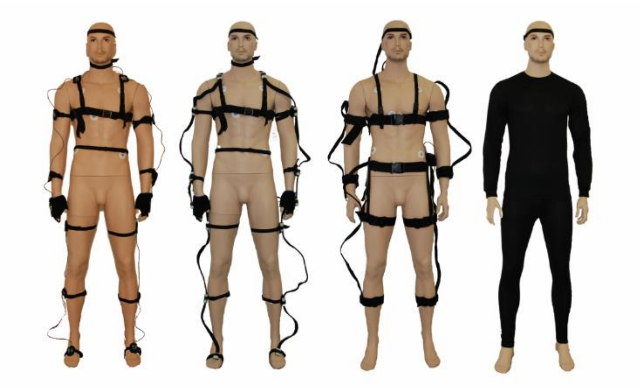

Fig. 3 Subsequent versions of smart clothing with sensing devices for remote continuous monitoring. From the left: I, II, III, IV(2013)

from multiple integrated measurement systems. It was initially created as a Human Motion Suit - novel, commercializable motion capture technology in the form of a low cost, wearable system. It performed synchronous motion capture measurements and enabled processing simultaneous motion data up to 50 people on one PC. It was based on developed at Silesian University of Technology (SUT) energy saving miniature sensors - Inertial Measurement Units (IMU), which can form a sensor network scalable up to 50 units, initially sewn into a fitted unencumbering costume, which can be worn under the clothing (Fig.3 IV). Sewing sensors into costume is very popular form of fitting in wearable clothing [10] but sensors often changes the position during activity. The last version of our smart clothing is more advanced and allows easy detach the measurements system and sensors and well as sustains long wash cycles, what makes it a tangible and fashionable solution to regular use. Clothing with wires in a ribbon form have been developed by the Institute of Textiles (IoT) from Lodz, Poland. Everything is sewn to thermal underwear. This construction provides the adhesion to the human body sensors and minimizes the undesirable movement sensors. In the IV-th generation of smart clothing the conventional cables were eliminated. In place of the internal fabric channels for conventional cables we use a specially designed four-tape in the form of a flat, linear elastic textile product. Prototype tapes are made using knitting yarn containing special silver-plated, coppery conductive monofilament (Fig.4). The IoT has developed a way of finishing the tape, whereby they get appropriate degree of elasticity.

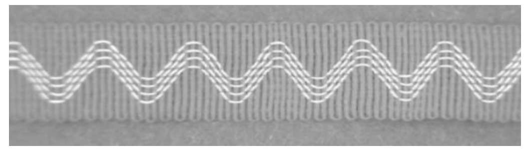

Fig. 4 Prototype tape with silver-plated, coppery conductive monofilament

Our small size, lightweight IMU sensors are targeted to sensors network (Fig.1). The IMU is able to work in a challenging dynamic environment, with calibrated stability (bias, scale factor, axial alignment) and process algorithms in hardware. The basic BAS version contains the motion capture system for kinematics measurements, hidden in clothing and formed from 16 IMU sensors. It also contains a kinetic measurement subsystem with two sensor insoles for registering information about subjects' partial weightbearing, pressure distribution and center of pressure (COP) during gait. We tested this kinematic-kinetic configuration in outdoor environment and proposed a general procedure for modifying simulation models of articulated figures, particularly useful when dealing with systems in time-varying contact with the environment [11].

The local control and transmission functions are integrated in the hub. The hub includes a microcontroller, SD memory, WiFi module, two CAN buses connecting to the IMU modules and other subsystems. The hub and the batteries are worn in a back pocket, where they least constrain the movements.

BAS it capable to incorporate other medical devices. The number of sensors IMU and their location depends on the specific task. It gives us the opportunity to create wireless sensor networks in any hierarchical or rigid configuration. In the maximum mode a multi-sensor BAS can cover the entire human body, with one sensor IMU assigned to one rigid body segment. In the minimum mode, it is possible to analyze a single human joint.

Scalability concerns the network and the costume. Network scalability means that a variable number of BAS units (currently up to 50) can be controlled within the MDE system. The costume scalability means that it can be made in several sizes, and a costume can have a different number of IMU modules, placed at predetermined locations depending on the measurement task. Also, MDE system and BAS can work with other sensors than IMU, and adding measurement sensors for ECG with dry electrodes, pulse oximetry, temperature is planned for the new version of the BAS costume.

The low energy objective is achieved by using a module that consumes only 20 mA@5V, which gives us 24 hours of continuous acquisition for a BAS costume with 16 IMU modules, and a 1.5Ah, 12V battery. The main BAS parameters are: IMU overall output rate is 200Hz after resampling and filtering (accelerometer-773Hz, gyro-100 Hz, megnetometer-200Hz) , CAN network bandwidth 500kbs, WiFi 802.11g @54Mbs, local storage 32 GB.

## IV. SAMPLE DEMONSTRATIONS

Tests were conducted in cooperation with OBRUM - member of Polish Defense Holding, with armored vehicle and soldiers on the ground. The equipment for the simulated training of crews has been extended by BAS, customized by using a stronger and more durable fabric. The training concerned a cooperation of a squad of soldiers on ground and an armored vehicle. Using the acquired motion data, and the recorded motion of the vehicle, such training exercise can be replayed and analyzed, which could lead to tactical improvements. Thanks to real time data streaming technology each soldier equipped with a BAS had direct feedback from the simulator engine in real time. We presented BAS with customized MMDE software, during International Defense Industry Exhibition, MSPO 2013, Kielce, Poland as well as during 11-th Wearable Technologies Conference 2014 in Munich, Germany. We also started cooperation with physicians on automatic gait and posture assessment in parkinsonism and dementia and rehabilitation programs and motor learning in neurodegenerative conditions with BAS.

## V. CONCLUSIONS

In the paper the concept and implementation of scalable, wearable sensor network embedded in smart clothing and integrated with distributed data processing and control system, for remote monitoring of physiological parameters were presented. It is not a ready-to-use solution with a closed set of functionalities. The presented platform is a way to create a dedicated solution for specific needs faster and cost-efficiently. We drew attention to the problems of discrete and remote measurements, and demonstrated Body Acquisition System – multisensory system with low power wireless module incorporated into smart clothing. We also presented software components supporting data acquisition, processing, analysis and data management. The future research and development of the basic hardware configuration will include the correction of integration drift of 3D accelerators and gyroscopes, optimization of local processing, and increasing effectiveness of data transmission between BASs. We will also improve software elements, automate tests of the system as well as software client functionalities in different configurations.

## ACKNOWLEDGMENT

This project has been supported by Applied Research Programme of the National Centre for Research and Development (project ID 178438 path A).

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## REFERENCES


1. Ullah S, Higgins H, Braem B, Latre B, Blondia C, Moerman I, Saleem S, Rahman Z and Kwak K.S (2010) A Comprehensive Survey of Wireless Body Area Networks: On PHY, MAC, and Network Layers Solutions, Journal of Medical Systems, 2010
2. Malik B and Singh V.R (2013) A survey of research in WBAN for biomedical and scientific applications. Health and Technology. doi:10.1007/s12553-013-0056-5
3. Touati F. and Tabish R. (2013) U-Healthcare System: State-of-the-Art Review and Challenges Journal of Medical Systems, 05/03/2013
4. Baig M. M, Gholamhosseini H. and Connolly M. J (2013) A comprehensive survey of wearable and wireless ECG monitoring systems for older adults. Med. Biol. Engineering and Computing, 51, pp.485-495
5. Patel S, Park H, Bonato P, Chan L. and Rodgers M (2012) A review of wearable sensors and systems with application in rehabilitation. Journal of NeuroEngineering and Rehabilitation. doi:10.1186/1743-0003-9-21
6. Vlasic D, Adelsberger R, Vannucci G, Barnwell J, Gross M. H, Matusik W & Popovic J (2007) Practical motion capture in everyday surroundings. ACM Trans. Graph., 26, 35.
7. Kulbacki M, Segen J, Nowacki J.P (2014) 4GAIT: Synchronized MoCap, Video, GRF and EMG Datasets: Acquisition, Management and Applications. ACIIDS (2) 2014, pp.555-564
8. Filipowicz W, Habela P, Kaczmarski K, Kulbacki M (2010) A Generic Approach to Design and Querying of Multi-purpose Human Motion Database. ICCVG (1) 2010, pp.105-113
9. Kulbacki M, Janiak M, Kniec W (2014) Motion Data Editor Software Architecture Oriented on Efficient and General Purpose Data Analysis. ACIIDS (2) 2014, pp.545-554
10. McAdams E, Krupaviciute A, Gehin C, Dittmar A, Delhomme G, Rubel P, Fayn J, McLaughlin J (2011) Wearable Electronic Systems: Applications to Medical Diagnostics/Monitoring. Wearable Monitoring Systems 2011, pp. 179-203
11. Stepien J, Polanski A, Wojciechowski K (2012) A general on-the-fly algorithm for modifying the kinematic tree hierarchy. Applied Mathematics and Computer Science 22(2) 2012, pp.423-435


Author: Marek Kulbacki
Institute: Polish-Japanese Institute of Information Technology
Street: Koszykowa 86
City: Warsaw
Country: Poland
Email: kulbacki@pjwstk.edu.pl