mHealth @ UAH: Computing infrastructure for mobile health and wellness monitoring

New health care systems that integrate wearable sensors, personal devices, and servers promise to fundamentally change the way health care services are delivered and used.

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DOI: 10.1145/2539269

Mobile health (mHealth) represents the use of mobile wireless communication devices to improve health outcomes, healthcare services, and health research [1]. mHealth monitoring systems typically integrate wearable physiological sensors, personal devices like smartphones, and servers accessed over the Internet. They have emerged as a promising technology for real-time, unobtrusive, and continuous health and wellness monitoring of individuals during activities of daily living. Such systems promise to radically modernize and change the way healthcare services are deployed and delivered. They allow an individual to closely monitor changes in his or her vital signs and provide feedback to help maintain an optimal health and wellness status. When integrated with healthcare providers, these systems can even alert medical personnel when life-threatening changes occur. In addition, mHealth monitoring systems can be used for health monitoring of patients in ambulatory settings: as part of a diagnostic procedure, an optimal maintenance of a chronic condition, or a supervised recovery from an acute event or surgical procedure. They can also be used to monitor adherence to treatment guidelines (e.g., regular cardiovascular exercise) or to monitor effects of drug therapy.

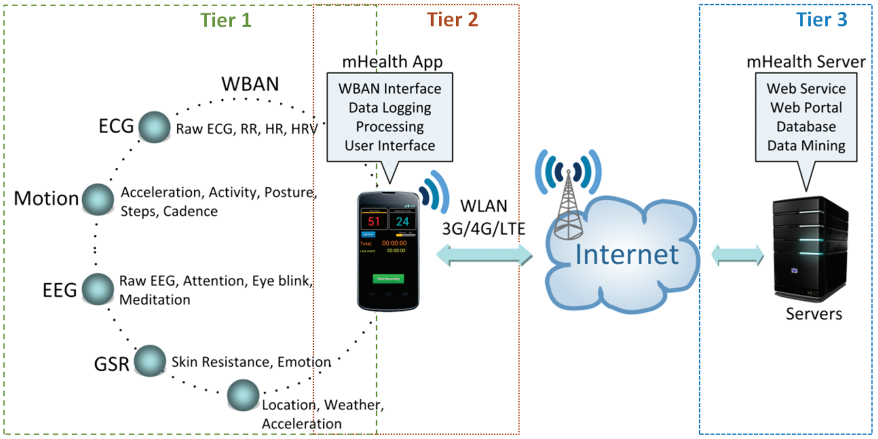
At the University of Alabama in Huntsville (UAH) an mHealth infrastructure, including both hardware and software components, was created to support research and education in the area of computer systems for mobile health and wellness monitoring. It is designed to help address critical design issues in the next generation of health monitoring systems—including their functionality, reliability, and energy-efficiency—to support creation of a repository with vital signs and physical activity parameters during normal daily activities, and to enable rapid prototyping of new monitoring applications.

HEALTH AT THE TOUCH OF A BUTTON

Convergence of smart biosensors, smartphones, and cloud computing services have enabled the development and proliferation of affordable mHealth monitoring systems capable of continuous health and wellness monitoring. Advances in sensor

technology have enabled miniature smart sensors to unobtrusively monitor physiological signals, body posture, type and level of physical activity, and environmental conditions. Physiological signals include heart electrical activity (electrocardiogram /ECG), muscle electrical activity (electromyography/EMG), brain electrical activity (electroencephalography/EEG), pulse and blood oxygen saturation (photoplethysmography/PPG), blood pressure, respiration/breathing rate, galvanic skin response (GSR), blood glucose level, and body temperature. In addition to the physiological signals, mHealth wearable monitors may include sensors that can help determine the user's location, discriminate between user's states (e.g., laying, sitting, walking, running), or sensors that can help estimate the type and level of the user's physical activity (e.g., low-, moderate-, or high-intensity aerobic activity). Since environmental conditions may influence the user's physiological state or accuracy of the sensors, mHealth monitors may integrate information about environmental conditions, such as: humidity, light, ambient temperature, atmospheric pressure, and noise.

Figure 1. Data flow in mHealth's three-tiered architecture.



Availability, affordability, and excellent performance make smartphones an ideal platform for mHealth applications. According to a report from August 2013, 225 million smartphones were sold worldwide in the second quarter of 2013, which represent an increase of 46.5 percent compared to the same period in 2012 [2]. With the recent proliferation of smartphones and tablet computers, the number of health monitoring and wellness applications has exponentially increased. According to a report from March 2013, more than 97,000 mHealth applications are listed on a variety of application stores [3]. Moreover, Google and Apple recognized this trend and made modifications in their operating systems to directly support health and wellness applications. The Android operating system incorporates a

Photograph by Warren Goldswain

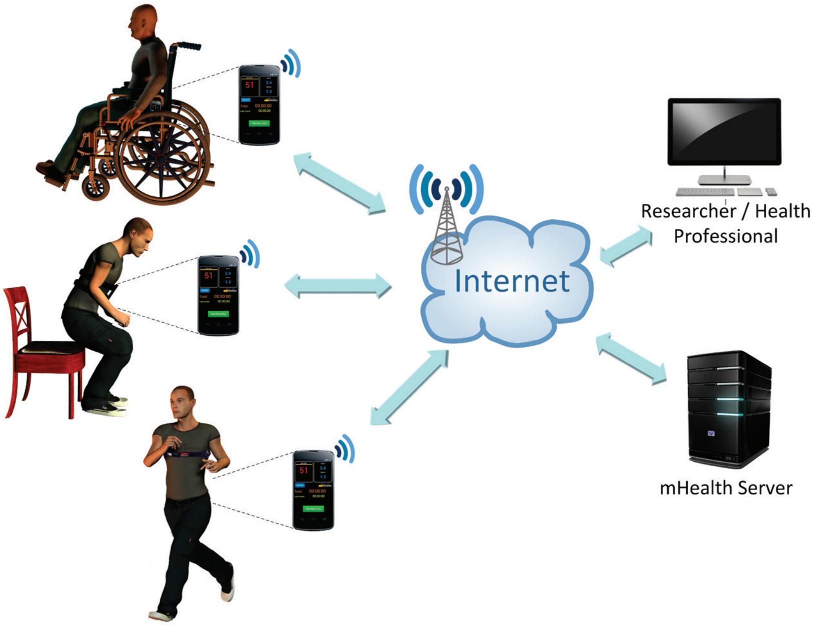
service that detects the user's current physical activity, such as walking, driving, or standing still. Apple went one step further with the latest iPhone 5S by designing and implementing a separate motion coprocessor to analyze user's activity from the motion sensors (accelerometer, gyroscope, and magnetometer). The availability of affordable smartphones and wearable devices, their widespread use, and consumer acceptance create new opportunities for users and healthcare professionals. An increasing number of users, who actively monitor their own health and fitness status, further underscores this trend [4].

MHEALTH @ UAH

The mHealth infrastructure at UAH is designed as a three-tiered architecture with wireless body area sensor networks and other physiological monitors at Tier 1, personal computing devices at Tier 2, and mHealth servers at Tier 3. This is represented in Figure 1.

Tier 1 consists of one or more body area networks (BANs) or body sensor networks (BSN) optimized for a specific health monitoring application. Each network integrates one or more wearable and intelligent sensor nodes. We rely on commercially available sensors and wearable monitors that sense vital signs, body posture, and environmental conditions. They range from inexpensive sensors (less than $100) intended for fitness monitoring applications to more sophisticated monitors designed for research (more than $2,000).

Figure 2. mHealth @ UAH.



For monitoring cardiac activity we use a range of monitors differing in

Figure 3. iTUG test phases and smartphone instrumentation of the subject.

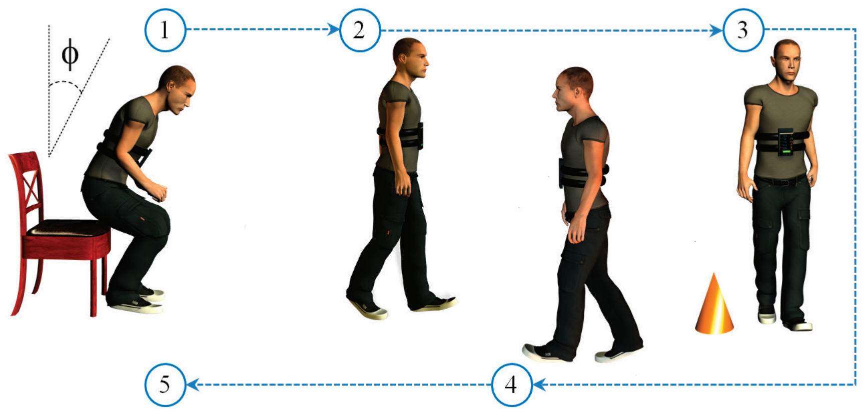


Figure 4. sTUG: Smartphone TUG Android application screen displaying the parameters of the TUG test.


imWell TUG

Total TUG Duration [s]
14.78

Sit to Stand Duration [s]
2.4

Stand to Sit Duration [s]
1.79

Angle [degree]
47.76

Max Angle Velocity [degree/s]
63.03

form factor, weight, functionality, accuracy, and cost. They range from fitness grade monitors that can report only an average heart rate to medical grade monitors that can report and record interbeat intervals (RR intervals) and electrocardiogram (ECG). For example, the Garmin ANT+ or Zephyr HxM heart rate monitors are a good choice for applications that have a long battery life and a small form factor as prime requirements. The Zephyr BioHarness 3 and Hidalgo Equivital 2 physiological monitors, capable of recording RR intervals and raw ECG signals, are a good choice for applications where accuracy and resolution are prime requirements. They also include additional sensors such as a three-axis accelerometer and a respiration sensor, and use the Bluetooth wireless interface for communication at Tier 2.

For monitoring brain electrical activity we use Zeo sleep monitors, NeoroSky MindSet EEG sensors, and Emotiv EEG neuoroheadsets. The Zeo sleep monitor is a low-power headband with a single channel EEG intended for sleep studies. The MindSet EEG provides a single channel EEG in the form of a wireless headset, whereas the Emotiv EEG headset offers 14 channels of EEG sampled, filtered, and reported through Bluetooth to a custom application.

For monitoring physical activity, body posture, and transitions we use a range of commercially available sensors, such as the Garmin ANT+ foot pod sensor and the Garmin ANT+ bike sensor or inertial sensors featuring accelerometers, gyroscopes, and magnetic sensors. The foot pod sensor measures the number of steps made and speed during walking/running, while the speed/cadence sensor measures cycling speed. Both sensors use the low-power ANT+ wireless interface for communication at Tier 2.

Personal devices like smartphones can also be utilized for sensing body posture, physical activity, and environmental conditions. For example, a Google Nexus 4 smartphone includes a three-axis accelerometer, a three-axis gyroscope, a three-axis magnetometer, a barometer, a proximity sensor, an ambient light sensor, a GPS (Global Positioning System), and two cameras.

Personal applications running on a personal device (e.g., Android and Apple/iOS smartphones, tablets, or personal computers) represent Tier 2 of the proposed architecture. Applications are designed to facilitate (1) interface and management of a variety of sensors in the sensor network; (2) data retrieval from individual sensors, data logging, and analysis to extract health status information; and (3) user interface providing real-time feedback with health parameters and recommendations (e.g., guided rehabilitation or exercise). The collected health status information is periodically uploaded to the mHealth servers over the Internet. The majority of applications are developed for Google's Android and Microsoft Windows operating systems.

A group of servers providing storage, access, visualization, and support for data mining of physiological records forms Tier 3 of the mHealth infrastructure. The servers are running a free operating system, Ubuntu Server, and are designed and implemented to work as virtual machine appliances in either open source VM VirtualBox or proprietary VMWare environment. This approach offers flexibility and easy deployment and migration to new physical platforms or even to cloud infrastructure. Tier 3 of the mHealth infrastructure is composed of three main components: mHealth Database, Web API, and Web Portal. System architecture and sample applications are presented in Figure 2.

The mHealth database is developed using Oracle's MySQL relational database. The open-source database is specifically designed to support efficient storage of a variety of physiological records and record annotations. Each record has information about the subject, equipment used to collect records, and conditions under which the data are recorded. Physiological records can be organized by application type, and each record is precisely time-stamped. In addition, the database provides support for management and guidance of a variety experiments in research environment. Experiments can be conducted using a specific protocol and have authorized investigators, a list of sessions with individual participants, and individual physiological, activity, and multimedia records.

The Web API component is designed to be an intermediary between the personal devices and the mHealth database. It accepts data from personal devices and stores it into the database, and also allows personal devices to retrieve stored data from the database. Any action using Web API requires successful authentication. Upon a successful authentication, a Web session is created, allowing further execution of Web API requests without additional authentication. After a predefined period of inactivity, the session automatically expires and the authentication process has to be repeated.

The Web Portal component provides easy access to physiological data and its basic visualization. It requires only a Web browser to access a recorded session in the mHealth database. It is developed using the Sencha JS framework. Each authenticated user is allowed to access only a subset of data he/she is authorized to access. The user can easily visualize data by selecting the desired session and the particular signals inside the session.

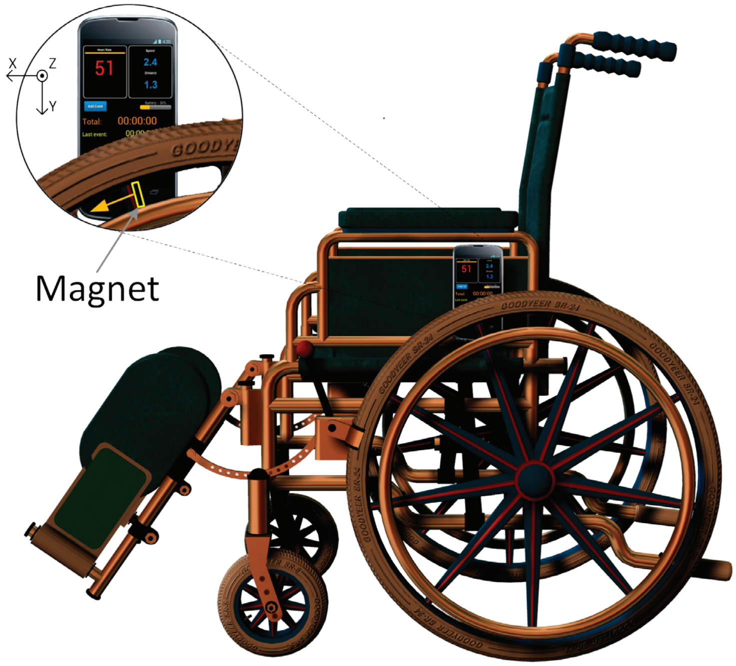
EXAMPLE APPLICATIONS

At UAH we originally developed two mHealth applications: sTUG and mWheelness. sTUG quantifies and automates a standard Timed-Up-and-Go (TUG) test used to assess mobility of individuals. mWheelness monitors physical activity of individuals who rely on wheelchairs for mobility.

Real-time quantification of TUG test. TUG is a frequently used clinical test for assessing balance, mobility, and fall risk in the elderly population and for people with Parkinson's disease. It is simple and easy to administer in an office, and thus can be used in screening protocols. The test measures the time a person takes to perform the following tasks: rise from a chair, walk three meters, turn around, walk back to the chair, and sit down. Longer TUG times have been associated with mobility impairments and increased fall risks. TUG duration is also sensitive to therapeutic interventions, such as in Parkinson's patients.

The availability of affordable smartphones and wearable devices and their widespread use and consumer acceptance create new opportunities for users and healthcare professionals.

Figure 5. Smartphone instrumentation of a wheelchair.



We have developed a smartphone application called sTUG that completely automates the instrumented Timed-Up-and-Go (iTUG) test so that it can be performed at home [5]. sTUG captures the subject's movements utilizing a smartphone's built-in accelerometer and gyroscope sensors, determines the beginning and the end of the test and quantifies its individual phases, and optionally uploads test descriptors into the mHealth server.

A subject mounts the smartphone on his/her chest or belt and starts the application, as illustrated in Figure 3. The application records and processes the signals from the smartphone's gyroscope and accelerometer sensors to extract the following parameters that quantify individual phases of the iTUG: (a) the total duration of the TUG, (b) the total duration of the sit-to-stand transition, and (c) the total duration of the stand-to-sit transition. In addition, we extract parameters that further quantify body movements during sit-to-stand and stand-to-sit transitions, including the duration of sub phases, maximum angular velocities, and upper trunk angles. These parameters are recorded on the smartphone and optionally uploaded to the mHealth server. The application stops monitoring auto-

matically once it detects the end of the stand-to-sit transition. Figure 4 shows a report generated by the application at the end of a TUG test.

sTUG is developed for the Android operating systems and requires a smartphone with the accelerometer and gyroscope sensors running Android 2.3 or above. The application has been tested on a Nexus 4 smartphone, a Motorola RAZR M, and a RAZR HD.

We believe this application could be of great interest for older individuals and Parkinson's disease patients as well as for healthcare professionals. The procedure requires minimum setup (a chair and a marked distance of three meters) and inexpensive instrumentation (a smartphone running the sTUG application is placed on the chest or belt). The feedback is instantaneously provided to the user in a form of a report with the values of all significant parameters that characterize the TUG test. It is easy to use and users can take multiple tests in a single day at home (e.g., to assess the effects of drugs). With automatic updates to the mHealth server, caregivers and healthcare professionals can gain insights into overall wellness of the subjects. For example, they can assess the impact of therapeutic interventions (e.g., impact of drugs) by analyzing the parameters from multiple tests performed in a single day. Healthcare professionals and researchers can monitor and evaluate the evolution of a disease by analyzing the trends in the parameters collected over longer periods of time.

Real-time monitoring of activity of wheelchair users. Physically inactive individuals are almost twice as likely to develop coronary heart disease compared to those who exercise regularly. Recent estimates suggest the impact of physical inactivity on mortality risk is approaching that of tobacco as one of the leading causes of death in the able-bodied population. People with limited ambulatory skills who use wheelchairs for mobility are especially at high-risk for all inactivity-related diseases. For example, it has been reported that a person with a spinal cord injury (SCI) has a significantly greater risk of mortality from coronary heart disease (225 percent) than an able-bodied person. According to a 2005 U.S. Census Bureau's Survey, more than 3.3 million Americans use some type of wheelchair for mobility and with the aging population this number is likely to continue to grow.

In order to provide an affordable, reliable, and easy to use solution for monitoring the physical activity of users who rely on wheelchairs for mobility we developed a smart wheelchair [6]—a common wheelchair instrumented only with a smartphone that is used to track a user's physical activity. The system can record, log, display, and communicate information about the user's physical and heart activity during normal daily activities or exercise sessions. For monitoring the user's physical activity we utilized the smartphone's built-in sensors such as a magnetic sensor for monitoring wheelchair speed and distance traveled, an accelerometer for monitoring smartphone's orientation and wheelchair inclination, and a proximity sensor to determine whether the wheelchair is hand-propelled or pushed. In

Figure 6. mWheelness Android application screens.

☑ Wheelchair
Total Distance [mile] 0.029
Self Prop. Distance [mile] 0.029
Speed [mph] 1.129
Inclination [%] 6.9

☑ Zephyr BH3
Heart Rate [bpm] 80
Respiration Rate [bpm] 26
Calories 6.42

Climb [ft] 7.9/0.0

Total: 1:12
Last event: 1:12

addition, we employ a wearable chest belt to monitor and record the user's heart activity and energy expenditure. A smartphone application called mWheelness collects data from the sensors and performs periodic uploads to the mHealth server.

Figure 5 illustrates the proposed wheelchair instrumentation with a smartphone. The smartphone is placed in a holder on a side of the wheelchair. The smartphone's magnetic sensor senses the x, y, and z components of the magnetic field as illustrated in Figure 5. By placing a small magnet on the wheel, we induce a change in the magnetic field sensed by the magnetic sensor of the smartphone when the magnet moves over the smartphone. This change produces a characteristic signature in the magnetic field signals that can be sensed, recorded, and processed on the smartphone. By processing the magnetic field signals we can detect and timestamp an event, when the magnet moves right over the smartphone, which corresponds to one revolution of the wheelchair's wheel.

A smartphone's accelerometer measures proper acceleration and is typically used to keep the screen upright regardless of the smartphone orientation. In our setup we process the x, y, and z acceleration components to determine smartphone's orientation, i.e., whether it is placed in the wheelchair holder or not. Activity recording is enabled only when the smartphone is properly mounted on the wheelchair. In addition, the accelerometer data is used to determine slope of the wheelchair, which can further be used to determine vertical gain and loss during exercise.

A smartphone's proximity sensor is typically used to determine when the smartphone is brought up to the user's ear and usually acts as a binary sensor. In our deployment, the smartphone's proximity sensor is used to determine whether the user hand-propels the wheelchair or it is pushed. This information can be used to further qualify the user's activity.

Figure 6 shows one of the characteristic screens of mWheelness. The user starts recording physical activity and heart activity by pressing the start/stop recording button, although the processing of the signals from the magnetic sensor will not start before the smartphone is in the upright position. During an exercise session mWheelness displays current inclination, speed, and distance traveled. In addition, it displays information about heart activity.

Availability, affordability, and excellent performance make smartphones an ideal platform for mHealth applications.

The mWheelness application has been tested on several Android smartphones (Nexus 4, Motorola RAZR M, and HTC One X) in controlled and free-living conditions. The controlled experiments were conducted on a treadmill while varying speed and inclination. Distance traveled and inclination as reported by the application, were then compared against the corresponding parameters reported by the treadmill.

CONCLUSION

The infrastructure proved very effective in supporting research projects, course projects, and senior design projects in the exciting and emerging area of mobile health monitoring. More information about the mHealth infrastructure at UAH can be found at http://portal.mhealth.uah.edu. mHealth infrastructure developed and implemented at the University of Alabama in Huntsville was supported in part by NSF grant 1205439 *mHealth - Computing Infrastructure for Mobile Health and Wellness Monitoring*. Similar systems can be deployed at other institutions to support research and education and to enable students from different disciplines (e.g., computer science/engineering, medical, biomedical, nursing, and health sciences) work together and develop new exciting multidisciplinary health applications and services that may lead to improved quality of life and reduced cost of healthcare.

References

[1] Istepanian, R. S. H., Jovanov, E., and Zhang, Y. Guest editorial introduction to the special section on m-health: Beyond seamless mobility and global wireless health-care connectivity. *IEEE Trans. Inform. Technol. Biomed. 8*, 4, (2004), 405–414.

[2] Gupta, A., Milanesi, C., Cozza, R., and Lu, C. K. Market Share analysis: Mobile phones, worldwide, 2Q13. Gartner, Aug. 2013.

[3] Jahns, R.-G. and Houck, P. Mobile Health Market Report 2013-2017, research2guidance, Mar. 2013; http://www.research2guidance.com/shop/index.php/mhealth-report-2

[4] Quantified Self; http://quantifiedself.com/. [Accessed: 18-Jan-2013].

[5] Milosevic, M., Jovanov, E., and Milenkovic, A. Quantifying Timed-Up-and-Go test: A smartphone implementation. In *Proceedings of the 2013 IEEE International Conference on Body Sensor Networks* (Boston, MA, May 6-9). IEEE, New York, 2013, 302–307.

[6] Milenkovic, A., Milosevic, M., and Jovanov, E. Smartphones for smart wheelchairs. In *Proceedings of the 2013 IEEE International Conference on Body Sensor Networks* (Boston, MA, May 6-9). IEEE, New York, 2013, 404–409.

Biographies

Mladen Milosevic received his Dipl. Ing. Degree in electrical and computer engineering from the University of Belgrade Serbia and his Ph.D. from the University of Alabama in Huntsville in the area of wearable health monitoring. His areas of expertise include ubiquitous health monitoring, smartphone application development, software development, and physiological signal processing.

Aleksandar Milenković is associate professor of electrical and computer engineering at the University of Alabama in Huntsville, where he leads the LaCASA Laboratory (http://www.ece.uah.edu/~milenka). He received the Dipl. Ing., M.S., and Ph.D. degrees in computer engineering and science from the University of Belgrade, Serbia in 1994, 1997, and 1999. His research interests include computer systems architecture, embedded systems, and wearable health monitoring systems. Prior to joining the University of Alabama in Huntsville he held academic positions at the University of Belgrade in Serbia and the Dublin City University in Ireland. He is a senior member of the IEEE, its Computer Society, the ACM, and Eta Kappa Nu.

Emil Jovanov is an associate professor in the Electrical and Computer Engineering Department at the University of Alabama in Huntsville. He received his Dipl. Ing. (1984), M.Sc. (1989), and Ph.D. (1993) from the University of Belgrade. He is recognized as the originator of the concept of wireless body area networks for health monitoring and he is one of the leaders in the field of wearable health monitoring. Dr. Jovanov is a senior member of IEEE, and serves as associate editor of the *IEEE Transactions on Information Technology in Biomedicine* and *IEEE Transactions on Biomedical Circuits and Systems*, and as a member of Editorial Board of *Applied Psychophysiology and Biofeedback*. He is a member of the IEEE Engineering in Medicine and Biology Society (IEEE-EMBS) Technical Committee on Wearable Biomedical Sensors and Systems and a member of the IEEE Medical Technology Policy Committee. Dr. Jovanov has spent more than 25 years in the development and implementation of application specific hardware, software, and systems. His current research interests include ubiquitous and mobile computing, biomedical signal processing, and health monitoring.