Extended Summary

Enabling Effective Programming and Flexible Management of Efficient Body Sensor Network Applications

Giancarlo Fortino, Roberta Giannantonio, Raffaele Gravina, Philip Kuryloski, and Roozbeh Jafari

Abstract The paper [1] addressed and solved challenging issues that limited the wide diffusion of wireless body sensor networks (BSNs) in real life contexts by providing novel methodological and technological solutions that are both effective and efficient. In particular, the tackled issues primarily concern the programming complexity of BSN systems due to the lack of domain-specific high-level software abstractions. After analyzing and comparing the state-of-the-art solutions for BSN programming, and after eliciting the most important requirements for an effective BSN-specific software framework, which enable efficient signal-processing-intensive applications, we presented the SPINE (Signal Processing In-Node Enviroment) middleware, an open-source domain-specific programming framework designed to support rapid prototyping and flexible management of BSN applications. We notably described how SPINE efficiently addresses the elicited requirements while providing performance analysis on the most common BSN-oriented hardware/software sensor platforms. Effectiveness of SPINE was demonstrated through practical examples related to high-impact BSN applications (e.g. activity monitoring, physical rehabilitation, gait analysis, emotion and gesture detection) that were entirely developed using SPINE. Finally, the paper presented a novel development methodology for BSN applications that reuses the well-known Platform Based Design concepts and the SPINE platform.

Keywords — Design methods for wearable computing, human-centered applications, sensor-programming frameworks, signal processing in node environment (SPINE), wireless body sensor networks (BSNs).

1 Introduction, Motivation and Related Work

Wireless body sensor networks (BSNs) are collections of wearable (programmable) sensor nodes communicating with a local personal device (or coordinator): (i) sensor nodes have computation, storage, and wireless transmission capabilities, a limited energy source (i.e., battery), and different sensing capabilities (e.g. body motion, skin temperature, heart rate, skin conductivity, and brain activity) depending on the physical transducer(s) they are equipped with; (ii) the coordinator, which is typically a smartphone or a PC, allows for real-time monitoring as well as long-term remote storage and off-line analysis.

BSNs can actually enhance many human-centered application domains such as m-Health, e-Sport and e-Wellness, e-Emergency, e-Factory, and physical/virtual social interactive systems. However, BSN applications are hard to be developed mainly due to programming complexity: implementing real-time, power-efficient distributed signal processing algorithms on wireless sensor nodes that are very constrained in resources remains extremely challenging and complex. BSN applications are mainly developed following two main approaches: low-level programming and general-purpose middleware. However, while the former may be very efficient but time-consuming and error-prone, the latter may provide high effectiveness but poor performances.

In order to overcome the issues of such approaches, a novel domain-specific framework approach was defined to enable faster prototyping times and help realizing more effective and efficient applications in the BSN domain. The approach is centered on the SPINE (Signal Processing In-Node Enviroment) middleware. Before SPINE, only a few specific frameworks for BSN programming (e.g. Codeblue, RehabSpot and Titan) were proposed, mainly due to (i) the lack of standardization for BSN sensor node hw and sw platforms, (ii) the fact that BSN-based application domains were quite novel, and (iii) the application-driven low-level programming approach adopted by many BSN developers. However, they do not fulfill all the identified requirements for an effective BSN programming framework: programming effectiveness, system efficiency, system interoperability, system usability, and privacy support.

2 The SPINE Middleware

SPINE is an open-source middleware aiming to support the development of distributed signal-processing-intensive BSN applications through: (i) a wide set of pre-defined physiological sensors, (ii) in-node and on-coordinator signal-processing utilities, (iii) flexible application-level data transmission, and (iv) optimized heterogeneous network and resource management. Thanks to its well-designed modular architecture, SPINE allows easy integration of new custom-designed sensor drivers and processing functions, as well as flexible tailoring and customization of its built-in features. Great emphasis is on the reuse of software components to allow different end-user applications to configure sensor nodes at run-time based on the application-specific requirements so that the same embedded code can be used for several applications without reprogramming.

3 SPINE Technology, Performances and Applications

The variety of computers and mobile devices, sensor platforms (e.g. TelosB, Shimmer, SunSPOT, TI CC2530), sensors (e.g. accelerometers, gyroscopes, ECG), communication protocols (e.g. IEEE 802.15.4, Bluetooth, ZigBee), programming languages (e.g. ANSI C, nesC, Java, Android), and operating systems (e.g. TinyOS, Z-Stack, Android) supported by SPINE enables a great degree of heterogeneity that is highly required for developing many different BSN applications.

An extensive performance evaluation of the SPINE framework atop all the supported sensor platforms was carried out by measuring the execution time of signal-processing functionalities, memory usage of the framework, network bandwidth, and energy consumption under a common application profile (or benchmark). Performance results confirm the SPINE efficiency atop heterogenous platforms. Moreover, we implemented the benchmark using CodeBlue and Titan atop the TelosB sensor platform to compare the performance of the three frameworks: obtained results show that SPINE is able to deliver the best overall performance in terms of memory usage, network delay and bandwidth, and particularly system lifetime.

In the paper, we also presented six prototypical SPINE-based BSN applications: activity recognition, physical rehabilitation, gait analysis, Kcal expenditure, emotional stress detector, and handshake detection. These applications configure SPINE differently, through minimal hw/sw customization and extension, to meet their specific requirements; however, the same basic hardware devices, and node-side and coordinator-side software have been exploited in each application so boosting rapid prototyping.

4 PBD-oriented Methodology

In the context of BSNs, the design of systems usually follows a *bottom-up* approach such that systems are developed choosing the hardware components first, then the communication protocols, and, finally, implementing ad-hoc applications on top of the underlying infrastructure. Alternatively, the *top-down* approach is adopted when designers choose to start from the high-level application requirements and map them to an application-level framework, i.e., a set of programming abstractions and APIs, without any intrinsic assumptions on the underlying protocol stacks and hardware platforms.

We defined a novel method - the SPINE-based design methodology (SPINE-based DM) - to support both bottom-up and top-down BSN system design to have reliable systems, system efficiency, and true interoperability between different applications, as well as between different implementation platforms. SPINE-based DM relies on the well-known Platform Based Design (PBD). In particular, we identified three layers of abstraction and corresponding platforms (that, differently from PBD, are semi-instatiated with SPINE): the Service Platform at the application layer, the Protocol Platform to describe the protocol stacks, and the Implementation Platform for the hardware devices. Each design integrates an instance of the three layers, thus containing both application, protocol and device layers. In particular, each design is a complete instance of the BSN system under-development at a given refinement step: high-level design, detailed design, or implementation. According to key system parameters, each step can be evaluated: while an implementation step performance can be experimentally evaluated, high-level and detailed design performance should be estimated through analytical/simulation tools. The application of SPINE-based DM is driven by an associated process schema.

5 Conclusions

Releasing SPINE as an open-source framework, along with a dedicated website and developer mailing list (http://spine.deis.unical.it) was very helpful for creating a community of both academic and industrial actors: contributors to the code and users of the framework. Feedback from the community was precious to highlight pros and cons and for the SPINE continuous evolution.

To sum up, our paper provided the following main research and technical contributions:

1) Elicitation of the fundamental requirements to fulfill for developing effective and efficient BSN-specific programming frameworks;

2) Design and implementation of the SPINE middleware, characterized by: (i) modular, configurable and extensible architecture and programming APIs (that provide sensor sampling, in-node data processing, sensor configuration at run-time, node synchronization, duty-cycling mechanisms, application-level communication protocols, and high-level processing) atop heterogeneous sensor platforms and, (ii) higher performance compared to correlated frameworks;

3) Different proof-of-concept prototypes, requiring different sensing and signal-processing capabilities, to show the SPINE effectiveness;

4) Definition of a novel SPINE- and PBD-based design methodology to systematically drive the development of BSN systems.

REFERENCES

[1] G. Fortino, R. Giannantonio, R. Gravina, P. Kuryloski, R. Jafari, "Enabling Effective Programming and Flexible Management of Efficient Body Sensor Network Applications," Human-Machine Systems, IEEE Transactions on, vol. 43, no. 1, pp. 115-133, Jan. 2013.

Giancarlo Fortino is currently Associate Professor of Computer Engineering at the Dept. of Informatics, Modeling, Electronics and Systems (DIMES) of the University of Calabria (Unical), Rende (CS), Italy. He has a Ph. D. degree and Laurea (MSc+BSc) degree in Computer Engineering from Unical. He holds the Italian Scientific National Habilitation for Full Professorship and is Guest Professor at the Wuhan University of Technology, China. He has been also Visiting Researcher and Professor at the International Computer Science Institute (Berkeley, USA) and at the Queensland University of Technology (Australia), respectively. His main research interests include agent-based computing, wireless sensor networks, pervasive and cloud computing, multimedia networks and Internet of Things technology. He authored over 230 publications in journals, conferences and books. He is the founding editor of the Springer Book Series on "Internet of Things: Technology, Communications and Computing", and currently serves in the editorial board of IEEE Transactions on Affective Computing, Journal of Networks and Computer Applications, Engineering Applications of Artificial Intelligence, Information Fusion. He is co-founder and CEO of SenSysCal S.r.l., a spin-off of Unical, developing innovative sensor-based systems for e-health and domotics. He is a Senior Member of IEEE.
Contact him at g.fortino@unical.it.

Roberta Giannantonio works in the Open Innovation Research Department of Telecom Italia. She graduated in Telecommunication Engineering at Politecnico di Torino in 2004 and then joined Telecom Italia being involved in research projects about Wireless Technologies and Internet of Things. She has been responsible of the SPINE open source project for distributed signal processing in Wireless Sensor Networks with special interest in wearable sensors. She is currently involved in research activities about Internet of Things and swarm intelligence with special interest into mobile application scenarios. She is author of patents and papers about wireless technologies and she holds the Project Management Professional PMP® certification.
Contact him at roberta.giannantonio@telecomitalia.it

Raffaele Gravina is currently serving as PostDoctoral Research Fellow in Computer Engineering at the University of Calabria, Italy. He received the PhD degree in computer engineering from the University of Calabria, Italy, in 2012. He is the main designer of the SPINE Framework and responsible for the open-source contributions.
His main research interests are focused on high-level programming methods for wireless Body Sensor Networks (BSNs), integration of Cloud computing with BSNs, and signal processing for human physiological signals. He is author of more than 30 papers in international journals and conferences. He spent two years as researcher at the Telecom Italia WSN Lab at Berkeley, California. He is involved in several research projects on WSNs, including AD-PERSONAS, MAPS and the REWSN Cluster of CONET FP7. He is co-founder of SenSysCal S.r.l., a spin-off of Unical, developing innovative sensor-based systems for e-health and domotics.
Contact him at rgravina@deis.unical.it

Philip Kuryloski is currently Senior Software Engineer at Pivotal Labs, San Francisco Bay Area. He received the Ph.D. degree in electrical and computer engineering from Cornell University, Ithaca, NY, in 2009. He was a Postdoctoral Researcher with the University of California, Berkeley. His research interests include the design and development of privacy and security features for wireless net-

worked sensing systems.
Contact him at philip.kuryloski@gmail.com

Roozbeh Jafari is an associate professor at UT-Dallas. He received his PhD in Computer Science (UCLA) and completed a postdoctoral fellowship at UC-Berkeley. His research interest lies in the area of wearable computer design and signal processing. His research has been funded by the NSF, NIH, DoD (TATRC), AFRL, AFOSR, DARPA, SRC and industry (Texas Instruments, Tektronix, Samsung & Telecom Italia). He has published over 100 papers in refereed journals and conferences. He is the recipient of the NSF CAREER award (2012) and the RTAS 2011 best paper award. He is an associate editor for the IEEE Sensors Journal, IEEE Journal of Biomedical and Health Informatics and IEEE Internet of Things Journal. He is a Senior Member of IEEE.
Contact him at rjafari@utdallas.edu