Towards Sensing Information Systems

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Abstract

Recent advances in the field of pervasive computing, including the approaches and technologies related to Wireless Sensor Networks (WSN), Internet of Things (IoT) and Cyber Physical Systems (CPS) are changing the way we perceive computing capability. Although the scientific communities have already started to discuss about the visionary concepts that will exploit these advances, such as Sensing and Liquid Enterprise, the truly smart and interoperable CPS networks are still confined to the 'valley of death' - between prototyping and mass-production. In this position paper, we propose the concept of Sensing Information System, a novel paradigm that will facilitate the transformation of CPS to Cyber Physical Ecosystems - borderless technical environments in which the devices will become capable to sense, perceive, decide and act, based on the external, common behavioural and context models. A case study is used to demonstrating the use of Sensing Information Systems for extended clinical workflows.

Keywords: Information Systems, Sensing Enterprise, Internet of Things, Future Internet, Cyber Physical Ecosystems.

1. Introduction

In today's dynamic and volatile global environment, businesses need to acquire agility in order to cope with, promptly adapt to, and ideally thrive on changes. The Sensing Enterprise (SE) concept and properties, supported by the paradigms of the Internet of Things (IoT) [2], Cyber-Physical Systems [9] and Future Internet Enterprise Systems [3], have the potential to become essential enablers towards an agile business, displaying awareness, perceptivity, intelligence and extroversion.

This transformation is expected to create new opportunities for the dynamic management of the inherently complex environments in which highly diverse enterprises connect and collaborate in typically short-lived supply chains for very specific purposes - for example, for *promptly* delivering a low number of highly customized products and services.

The SE concept will exhibit universal, on-demand interoperability of enterprises, achieved with a minimum needed commitment to change and adapted to the collaboration conditions. Naturally, the enterprise's (information and other) systems must facilitate, support and importantly, also participate and thus reflect this transformation.

In this paper, we propose the concept of 'Sensing' Information System (SIS) as a main interface of the SE to its environment. The paper presents the conceptual overview of the key requirements for SIS while taking into account new circumstances in which IS operation takes

place and its key capabilities for the awareness property. The SIS should be capable of seamlessly sense and perceive various stimuli, make autonomous and purposeful decisions and finally, act upon these decisions as appropriate. Actually, this anthropomorphic consideration of the future SISs implies that they will become inherently generic; thus, the capability of the envisaged Sensing ISs to process data for a specific purpose will be defined by the internally and / or externally located behavioural and functional models and the models of the internal and / or external contexts in which they process this data.

2. The Sensing Enterprise

As the economy and society are becoming increasingly networked and digital, there seems to be a need to redefine the notion of enterprise, especially as new social and technology tools are provided by recent advances in new research paradigms, such as the above-mentioned IoT, CPS, Future Internet Enterprise Systems and others. Such paradigms facilitate the pervasiveness of the enterprise, blurring its traditional boundaries to the point where internal and external stimuli (coming from within and outside of the enterprise) cannot be readily distinguished. As pervasiveness implies a federation of processing capabilities and knowledge resources, the new paradigms will also make collective intelligence more accessible and coordinated.

In an attempt to reconsider the notion of the enterprise, the FInES cluster [4] has identified several so-called 'Qualities of Being' as necessary properties of the future enterprise. They were: humanistic, community-oriented, cognizant, people-centred, inventive, agile, environmentally aware, and 'glocal' (with local and global perspective) [ibid.]. An enterprise displaying the above properties would become a so-called Sensing Enterprise (SE).

The SE is also described as "an enterprise anticipating future decisions by using multi-dimensional information captured through physical and virtual objects and providing added value information to enhance its global context awareness" [9]. In fact, it is not characterized only by awareness (as the term implies), but also by decentralized or ultimately, even collective intelligence. This does not only concern collaboration in decision making, but also purposefulness evaluated in its environment. Therefore, an SE is in fact a social enterprise, sometimes also described as 'liquid' to suggest its pervasiveness.

The 'liquid' character of the SE is supported by the anticipation that sensors will become a commodity in the future [13]; thus, the ownership of an enterprise on the sensors will not necessarily restrict other organizations to provide value-added services, based on observations of these sensors. Santucci et al. point out that "the Sensing Enterprise will be a sort of radar in perfect osmosis with an ecosystem of 'objects' supported by several private area networks and delivering in real time a wealth of unstructured data, not only more data but also new data" [ibid.].

2.1. Cyber-Physical Systems

In terms of technical architecture, the SE is considered as a system-of-Cyber Physical Systems (CPS), where these CPSs do not necessarily operate within the boundaries of the enterprise, nor even in its domain of interest or operation. Conversely, an SE may encompass the CPSs owned and governed by the other enterprises.

Cyber Physical Systems are autonomous, functional systems in which the collaborating computational elements are controlling the physical devices, by exploiting data gathered from the different sensors and other devices, which operate in the environment of these elements [9]. CPS research is a highly interdisciplinary area which combines knowledge and expertise in the fields of embedded systems, robotics, Wireless Sensor Networks (WSN), integration and interoperability, Knowledge Management and many others.

CPS are today considered as one of the key technological pillars for addressing many different societal challenges in the fields of urban infrastructure (e.g. smart cities), energy (smart grids), healthcare (smart hospitals), transportation (smart roads), etc.. It brings together automation and intelligent decision making for the benefit of improved safety, quality of life,

security, efficiency and productivity. Since late 2006, US National Science Foundation (NSF) has pushed CPS as a key research topic [15]; in 2014, through the Horizon 2020 program, the European Commission (EC), invests more than 600 MEUR[1] in the research related to Smart CPSs and new Information and Communication Technology (ICT) platforms for their development and implementation. The main goal is to improve Europe's innovation capacity in order to evolve today's embedded systems to more autonomous, more intelligent, pervasive and generic CPSs.

The pervasiveness and technical diversity of a CPS makes its high complexity inherent. For this reason, CPSs are usually specialized by design to individual application fields. Currently however, incoherent design and lack of unifying models typically prevent different, albeit functionally or geographically intersecting CPS to interoperate, and thus, to collaborate.

3. Sensing Information Systems

Sensing Information Systems can be considered the interfaces of the SEs towards their environment. They are deployed in the devices which form the CPSs, implement their processing capabilities and must be intrinsically interoperable, in order to enable the collective intelligence purported by the SE concept (see Fig. 1).

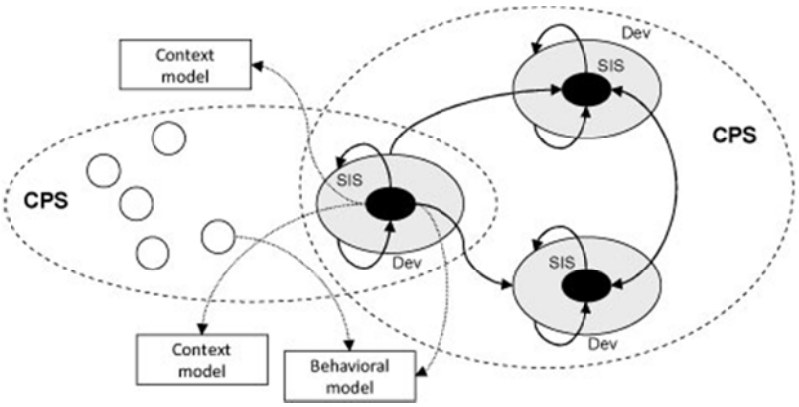

Fig. 1. Illustration of the SIS-driven Cyber Physical Ecosystems

Therefore, the design and architecture of the traditional information systems must be evolved in order to address the new requirements arising from the need to achieve pervasiveness, portability and context-awareness. We identify these new requirements as autonomy, portability and awareness, as argued below.

With the introduction of new computing elements (e.g. devices) that represent the core units of the future SEs, the traditional concept of IS deployment will need to take into consideration new and typically ubiquitous platforms. Hence, one of the most important challenges relating to the pervasiveness of SIS will be their autonomy, especially in terms of reliability and maintenance issues. These new computing elements will be deployed on a variety of hardware platforms, matching a variety of purposes. The key consequence of such new circumstances is the emerging need to achieve a seamless portability of the future SIS. This leads us to anticipate that the functional requirements of one future system will not be intrinsically embedded in its design. Instead, what was earlier considered as business logic tier of the conventional ISs will now be based on the deployment and use of common and shared behavioural models, accessible on IoT. Finally, all these elements operate in varying conditions and environments. Hence, an SIS needs to have capabilities to:

- Sense the physical environment of its device and other devices in its environment;
- Interact with the physical environment of its device and other devices by using its (their) actuation capabilities; and
- Exchange data, information and knowledge with SISs of other devices in its environment.

[1] Call H2020-ICT-2014-1, Topic: Smart Cyber-Physical Systems.

The above capabilities depend on the context models that will facilitate the context-awareness. Formal modelling of the contexts in which one system (or the device) operates will consider its surrounding environment, including technical, social, spatial aspects and interfaces of the systems and people with which it interacts. As these formal models are developed and stored externally, the SIS must also implement the reasoning strategies and techniques (e.g. based on Web Ontology Language (OWL/DL) reasoning), which will enable it to automatically infer the context in which it operates.

3.1. Sensing Information Systems Capabilities

In order to access, combine, use and act upon the extensive, multi-dimensional and multi-modal data (now at the disposal of a liquid enterprise), SISs needs to achieve and maintain capabilities to seamlessly sense this data, perceive its meaning, make decisions and articulate a response - whether this articulation refers to acting (actuating), requesting the additional data, transferring an information to another enterprise, etc.. The stimulus for this cycle may originate from within, or outside the SIS and within, or outside its domain of interest.

The cycle above can be explained in terms of semantic interoperation of two systems. In order to illustrate this cycle, we extend Sowa's [14] formal definition of semantic interoperability of systems; thus, a system S is semantically interoperable with system R, if and only if the following condition holds for any stimulus p that is articulated by S and sensed by R: For every statement q that is implied by p in the system S, there is a perception of p, namely q', in the enterprise R that: (1) is implied by p in the system R, and (2) is logically equivalent to q (see Fig. 2). This definition is represented in controlled natural language below:

$$
\begin{aligned}
&\mathit{system(S)} \wedge \mathit{system(R)} \wedge \mathit{semanticallyinteroperable(S,R)} \Rightarrow \\
&\quad \forall p \, (\\
&\qquad \mathit{stimulus(p)} \wedge \mathit{articulated\text{-}by(p,S)} \wedge \mathit{sensed\text{-}by(p,R)} \wedge \\
&\qquad \forall q(\mathit{statement\text{-}of(q,S)} \wedge p \Rightarrow q) \\
&\qquad \exists q'(\mathit{perceived\text{-}by(q',R)} \wedge p \Rightarrow q' \wedge q' \Leftrightarrow q) \\
&\quad)
\end{aligned}
$$

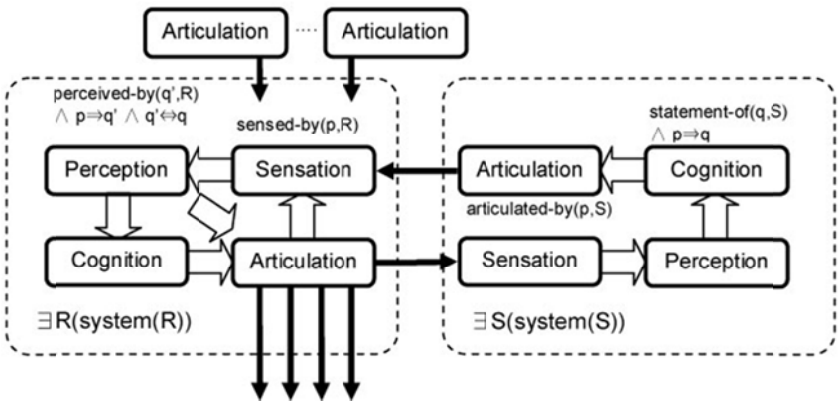

Fig. 2. Semantically interoperable Sensing Information Systems

Based on the assumptions above, we identify awareness, perceptivity, intelligence and extroversion as the key capabilities of the SIS [11, 17].

Although the core concept of SIS does not distinguish between the internal and external stimuli, there is a need to separately consider the self-awareness and environmental awareness of a SE. While the latter is crucial for exploiting the pervasiveness of the SE's SIS, the former is relevant for maintaining SE's multiple identities (e.g. towards suppliers' and customers' systems, but also on web or a social network), as it is suggested by the SE paradigm.

The pervasiveness of an SE extends the conventional domains of interest of an enterprise (e.g. typical channels for detecting new business opportunities). Hence, now one has to consider

not only the functional environmental awareness of an SIS, but also a *universal* awareness concerning observations of any stimuli, even from unknown and unanticipated sources. When arbitrary stimuli are taken into account, it becomes important for the SIS to achieve the capability to perceive any stimulus - be it multi-modal, multi-dimensional, discrete or continuous. Perceptivity is a capability of a SIS to assign a meaning to the observation from its environment or from within itself. Then, based on the perception, the SIS should be able to decide on the consequent action. This decision is a result of a cognitive process, which consists of identification, analysis and synthesis of the possible actions to perform in response to the "understood" observation. The intelligence also encompasses assertion, storing and acquisition of the behaviour patterns, based on the post-agreements on the purposefulness of the performed actions (much like a knowledge-based system).

The last desired attribute of a SIS, extroversion, is related to its willingness and capability to articulate the above action/s and demonstrates the SE's business motivation and/or a concern about its physical and social environment.

4. Scenario: Pervasive Personalized Healthcare Supply Chains

This section examines the potential benefits related to the application of SIS and related concepts to the field of personalized healthcare supply chains. More specifically, we refer to an 'extended clinical workflow' for cases where patient handling assumes the use of a custom medical product that needs to be designed, manufactured and installed (possibly by surgery) in a period of time comparable to the case of a standard medical product. A representative case of this scenario is custom orthopaedic implant design and manufacturing, often needed to address the possible risks of complications arising from geometrical differences between the specific patient bone anatomy and the limited standard implant sizes available.

The proposed patient-centric, extended clinical workflow [16] illustrated in Fig. 3 encompasses all activities of the clinical centre and other actors involved, from patient registration to transfer to other department/s or discharge.

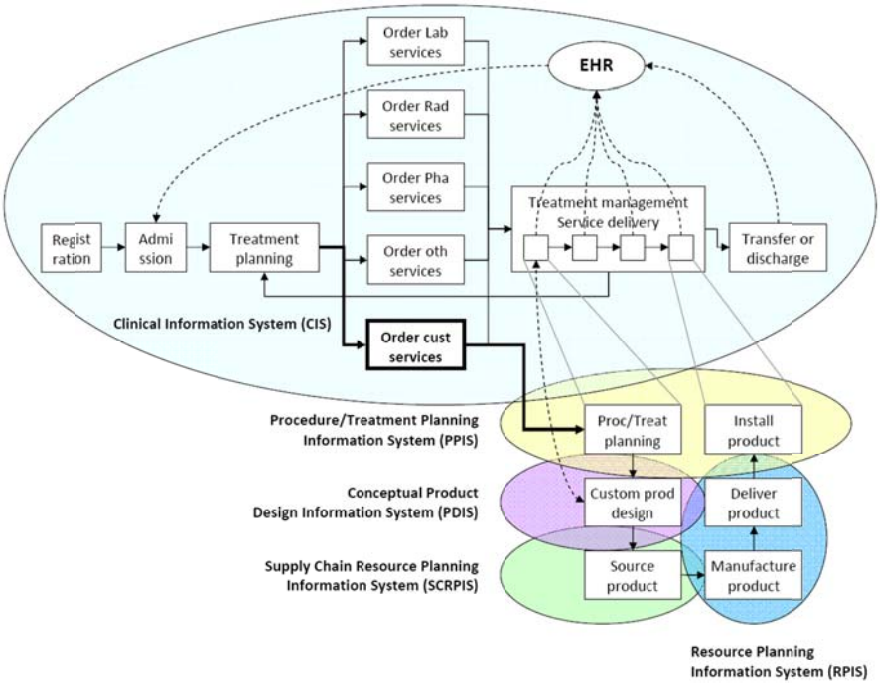

Fig. 3. Simplified representation of the extended clinical workflow

The extended clinical workflow integrates the conventional clinical workflow (represented at the top of Fig. 3 in a large ellipse), with the activities of the different actors, within or outside of Clinical Centre limits, involved in procedure and treatment planning, product design, sourcing, manufacturing and installation.

It is proposed that these activities are to be facilitated by corresponding ISs as illustrated in Fig. 3, with data converging to a patient Electronic Health Record (EHR), defined as the "[…] longitudinal electronic record of patient health information generated by one or more encounters in any care delivery setting" [7].

Workflow execution is typically based on the number of interoperations of the ISs, carried out in context of the previous agreements and respective commitments made by the relevant actors; however, the emerging pervasive computing approach is expected to minimize or remove the need to make such agreements. Device-centred collaboration, in contrast to system-centred interoperability, does however require the implementation of the required awareness, intelligence and actuation capabilities into autonomous, context-aware, collaborative and intelligent SIS. Importantly, this implies the reconsideration of the architecture of traditional healthcare IS design and collaboration [10].

4.1. SIS for Ubiquitous Healthcare

The concept of ubiquitous (or pervasive) healthcare [1, 12] supported by infrastructures relying on sensor networks and pervasive internet connectivity has emerged in recent years, creating significant opportunities for implementing the proposed SIS paradigm in practice.

Medical sensors combine transducers for spatial-temporal detection of electrical, thermal, optical, chemical, genetic and other signals with physiological origin with signal processing algorithms to estimate features indicative of a person's health status [8], e.g. pulse oximetry, respiration rate, temperature, heart rate, blood pressure, etc. The sensors also collect environment and logistics data (e.g. patients' locations, equipment locations) needed not only for detection, diagnosis and treatment of medical symptoms, but also for the management of the clinical workflow in which these activities occur. Namely, besides the vital signs information, other typical factors in the response to a potential clinical emergency are the patient's EHR and assignment of the respondent (doctor), based on physical location information [12]. Location and proximity sensing technologies can have significant effect in improving the workflow efficiency in hospitals [5]; for example, sensor networks can be used for automatic triage of patients for providing emergency care in large scale disasters, including tracking the health status of the first respondents [6].

Smart health monitoring devices, powered by the future SISs, should be able to actively participate in the clinical workflows by:

- sensing the changes in physiological parameters of the patients;
- perceiving the meaning of these changes, based on context models fed by data from the EHR of the individual patient and environmental sensors, and
- acting upon these perceptions, e.g. by automatically ordering laboratory, radiology or pharmaceutical services.

This approach would also facilitate reducing the complexity of traditional Clinical IS (CIS), by decomposing it into autonomous units forming the Cyber Physical System of the clinical centre. Such an approach would in addition increase the reliability of CIS by enabling redundancy. Namely, future SIS will be capable to use the behavioural models of other SISs on demand (for example, in case of urgency and failure of the responsible component).

The essential roles of the SIS concept are foreseen in the above-mentioned case of custom orthopaedic implant installation. These roles could be realized in the different phases of the extended workflow, with potential scenarios as indicated below.

The extended clinical workflow paradigm suggests that the successful treatment of some medical disorders could significantly expand the range of actors (and their supporting ISs) displaying the capabilities required to heal the patient. For example, in case of the orthopaedic implants, this may include advanced Computer Aided Design (CAD), Finite Element Analysis (FEA), rapid prototyping and manufacturing. As such capabilities cannot typically be found in a Clinical Centre, there will be a need to research the market, reach the most suitable enterprises and then establish and maintain seamless interoperability between their respective systems. The projected SIS capability to sense digital stimuli (e.g. from social networks or supply network platforms) is envisaged to facilitate this extension. The self-

awareness property will enable SIS to create multiple (agent-alike) identities that will be capable to actively pursue the sensed collaboration opportunities, even by engaging into negotiation processes with other systems, driven by motivations expressed in context models. In the extended clinical workflow (see Fig.3), this role is given to SCRPIS, which need to be enable to sense the collaboration prospect, including the corresponding RPIS, query the relevant information (e.g. availability, cost, etc.) from RPIS of the new or registered partners and potential actors of the specific workflow's instance.

The CPS and corresponding SIS infrastructure of the Clinical Centre could be also used for the benefit of the partners, involved in the engineering of the implant. For example, the design team could continuously monitor the status of the patient's bone, through the access to a smart immobilization device, and hence become capable to adapt the design decisions to the current circumstances. This approach could be extended to pre-hospital care, where first aid could install a smart traction splint, able to communicate via public wireless connectivity infrastructure. In this case, the smart immobilization device hosts a SIS which interacts with CIS (see Fig.3) which eventually delivers the relevant information to CAD systems of the designers, through the interoperability infrastructure.

The role of SIS in the exploitation phase, namely outside the extended clinical workflow, is also foreseen. The future SIS-embedded smart implants will be capable not only to sense e.g. the stresses occurring at the bone-implant joints and dislocations of the reference points, but also to perceive and interpret critical changes based on the context information, articulate this observation in messages and distribute it to its environment. Then, this information can be used for the improved design, better selection of materials, etc.

It is obvious that the concept of SIS will contribute to increasing collaboration in the extended clinical workflow, through reducing the amount of needed pre-agreements for the relevant systems' interoperations. The Clinical Centre demonstrating the above described capabilities, realized by their SIS, would become a truly sensing and liquid enterprise, with the technical infrastructure deployed through the different CPSs that can easily merge and combine with other CPSs, forming a Cyber Physical Ecosystem for personalized healthcare.

5. Conclusions

The rapid advance of CPS technologies and continuous miniaturization and commoditization of the relevant devices are strengthening the hopes and expectations of a next industrial revolution that will be capable to solve a wide range of societal challenges. In the emerging environment providing new avenues for IS deployment, the IS community needs to consider novel design and lifecycle requirements. In this position paper, we argue that the future SIS will need to display the properties of *awareness* (being able to sense the external or internal, multi-modal, multi-dimensional, continuous or discrete stimuli), *perceptivity* (being able to understand this stimuli, including the context in which this understanding occurs), *intelligence* (being able to decide on the perceptions by using internal or external behavioural models) and *extroversion* (being able to communicate with its environment).

One of the main arguments behind this proposition is related to addressing the various complexity issues arising from the new environment in which the future SISs will operate. It is proposed that SISs' complexity can be reduced by extracting and abstracting their behavioural and context descriptions and enabling their use and reuse as common, shared models. Such an approach will contribute to the need to define unifying standards and as such it will support the de-solidification of the systems themselves. Reducing the complexity of the systems will facilitate emerging efforts to develop more generic and hence, more portable system architectures.

Future research will seek to further develop the proposed concepts so as to enable the transformation of the CPS to 'smart environments', blurring the boundaries of CPSs and thus enabling an evolution towards Cyber Physical *Ecosystems*. This new paradigm will also facilitate the desired transformation of the traditional enterprises into a sensing, 'liquid' form.

Acknowledgement

This research is supported by the Ministry for Education and Science of Republic of Serbia (project VIHOS III41017).

References

1. Arnrich, B., et al.: Pervasive Healthcare – Paving the Way for a Pervasive,User-Centered and Preventive Healthcare Model. Methods Inf Med. 49(1): pp. 67-73 (2010)
2. Ashton, K.: That 'Internet of Things' Thing, in the real world things matter more than ideas. RFID, http://www.rfidjournal.com/articles/view?4986, (2009)
3. FInES:Future INternet Enterprise Systems - Research Roadmap 2025 (2012) http://cordis.europa.eu/fp7/ict/enet/documents/fines-researchroadmap-v30_en.pdf [Accessed July 10 2014].
4. FInES Cluster: Position Paper on Orientations for FP8: A European Innovation Partnership for Catalysing the Competitiveness of European Enterprises (2011) http://cordis.europa.eu/fp7/ict/enet/documents/fines-position-paper-fp8-orientations-final.pdf [Accessed July 20 2014].
5. Fry, E.A.Lenert, L.A.: MASCAL: RFID tracking of patients, staff and equipment to enhance hospital response to mass casualty events. AMIA Annual Symposium Proceedings Archive. Vol. 2005: pp. 261-265 (2005)
6. Gao, T., et al.: Wireless medical sensor networks in emergency response: Implementation and pilot results. Proceedings of IEEE Conference on Technologies for Homeland Security. 187-192 (2008)
7. Health Information Management Systems Society:HIMSS History (2013) http://www.himss.org/content/files/HIMSS_HISTORY.pdf [Accessed 2013]].
8. Ko, J., et al.: Wireless sensor networks for healthcare. Proceedings of the IEEE. 98(11) (2010)
9. Lee, E.: Cyber Physical Systems: Design Challenges. Technical Report No. UCB/EECS-2008-8, University of California, Berkeley (2008).
10. Noran, O.Panetto, H.: Modelling a Sustainable Cooperative Healthcare: An Interoperability-driven Approach Lecture Notes in Computer Science. 8186: pp. 238-249 (2013)
11. Noran, O.Zdravković, M.: Interoperability as a Property: Enabling an Agile Disaster Management Approach, In: 4th International Conference on Information Society and Technology (ICIST 2014): Kopaonik, Serbia (2014).
12. Rastegari, E., Rahmani, A., Setayeshi, S.: Pervasive computing in healthcare systems. World Academy of Science, Engineering and Technology. 2011(59) (2011)
13. Santucci, G., Martinez, C., Vlad-Câlcic, D.:The Sensing Enterprise (2012) http://www.theinternetofthings.eu/sites/default/files/%5Buser-name%5D/Sensing-enterprise.pdf 2014 [Accessed Jun 30 2014].
14. Sowa, J.: Knowledge Representation: Logical, Philosophical, and Computational Foundations. CA: Brooks/Cole Publishing Co. (2000)
15. Wolf, W.: The Good News and the Bad News (Embedded Computing Column). IEEE Computer. 40(11): pp. 104-105 (2007)
16. Zdravković, M.Trajanović, M.: On the extended clinical workflows for personalized healthcare. International IFIP Working Conference On Enterprise Interoperability (IWEI 2013), LNBIP 144: pp. 65-76 (2013)
17. Zdravković, M., Trajanović, M., Panetto, H.: Enabling Interoperability as a Property of Ubiquitous Systems: Towards the Theory of Interoperability-of-Everything, In: 4th International Conference on Information Society and Technology (ICIST 2014): Kopaonik, Serbia (2014).