On Pervasive Healthcare Information Systems in the Internet of Things

Milan Zdravković
LIPS, Faculty of Mechanical Engineering in Niš, University of Niš, Serbia
E-mail: milan.zdravkovic@ masfak.ni.ac.rs

Ovidiu Noran
School of Information and Communication Technology, CEARM, Griffith University, Australia
E-mail: O.Noran@griffith.edu.au

Miroslav Trajanović
LIPS, Faculty of Mechanical Engineering in Niš, University of Niš, Serbia
E-mail: milan.zdravkovic@ masfak.ni.ac.rs

Abstract

In the current quest for personalized and omnipresent healthcare required to address new emerging population health challenges, the localised, legacy concept of healthcare information systems is no longer expressive enough to address the complex interrelationships of the increasingly diversified technical environment in which the clinical processes occur. Thus, traditionally healthcare information systems architecture considered only clinical information systems and healthcare facilities; however, as the Internet-of-Things vision becomes a reality, an exponential number of mobile devices, sensors, tags and other identifiable resources with communication and processing capabilities will need to be added to the big picture. In such complex circumstances, the concept of interoperability also needs to evolve from the original concept involving pre-committed information systems to the capability of each information system to autonomously sense, interpret, understand and act upon arbitrary messages received from potentially unknown senders. Therefore, in this paper we propose an evolved concept of interoperability as a property of a system, more suitable to tackle the modern context of ubiquitous healthcare information systems. After defining the new problems faced by healthcare and concise review of the ubiquitous computing in the domain, we elaborate on the enabling factors for interoperable information systems involved in pervasive healthcare. Subsequently we attempt to assess and exemplify the impact that a novel Interoperability as a Property (IaaP) paradigm would have on the healthcare information systems' landscape.

Keywords

Health Information Systems, Ubiquitous Computing, Internet of Things, Interoperability as a Property

INTRODUCTION

The contemporary healthcare landscape is confronted with several major emerging challenges. Firstly, there is a pronounced lack of capacity in clinical centres, especially in regards to prevention and early detection. This issue is aggravated by worldwide demographic changes such as population aging due to increased longevity and eradication of some serious diseases, resulting in significant social security and healthcare challenges (International Labour Organisation 2009). Thus, the continuous monitoring and care required by the aged but also by children and chronically ill augments the issue of overloaded clinical environments where many hospitals nowadays often operate at, or over capacity. Ko et al. (2010) propose the shift from a centralized, expert-driven crisis-care model to one based on prevention and early detection that would be implemented both in homes and clinical centres. This approach requires proper long-term cooperation of healthcare providers, which is a non-trivial issue due to their typically pronounced heterogeneity and hierarchical structure.

Secondly, the occurrence of healthcare emergency situations such as pandemics appears to be on the rise as a result of natural and man-made disasters and increasingly involve drug-resistant strains (Waugh and Streib 2006). These acute medical incidents require short-notice close collaboration and context awareness of all healthcare providers involved in order to provide a prompt and efficient response, while also ensuring the safety of the response team participants.

Thirdly, thousands of patients die each year in hospitals due to medical errors, largely preventable by effective collaboration and continuous monitoring (Nembhard and Edmondson 2006). This brings about another major issue identified in the current healthcare domain: in the process of diagnosis and treatments the observations are sometimes inaccurate due to restricted information access to the full background of patient behaviour and lifestyle. Thus, current medical diagnostic facilities are typically insensitive to the context of the measurements or diagnostic actions, resulting in potentially biased observations - especially when atypical data patterns are observed.

Previous research (Noran 2012; 2013a; 2014; Zdravković et. al 2014) has described and detailed components of a cross-disciplinary approach based on the Information Systems (IS), Enterprise Architecture, Collaborative Networks and Interoperability schools of thought towards achieving Collaborative Healthcare Information Systems. This paper takes that research further by analysing the crucial impact of the impending ubiquitous computing and Internet-of-Things (IoT) paradigms on IS interoperability and implicitly on the collaboration capability of the healthcare providers' IS-es. Thus, the research questions behind the work presented in this paper are: a) what is required to enable a future IoT-compatible healthcare IS interoperability concept and b) how such a concept would affect the healthcare IS landscape. The methodology for addressing these questions builds on a synthesis of previous theoretical and practical work related to the development of systems interoperability concepts. Based on an anthropomorphic consideration of system behaviour, this rich interoperability body of knowledge is used to devise a novel approach to the definition of interoperability, seen now as the property of a *single* system. The impact on the healthcare IS landscape is also discussed in order to validate the proposed concepts and define avenues of further research.

UBIQUITOUS COMPUTING IN HEALTHCARE INFORMATION SYSTEMS

The last years have seen the emergence of the ubiquitous healthcare concept supported by an information technology (IT) infrastructure relying on devices displaying pervasive internet connectivity, such as Wireless Sensor Networks (WSNs). Thus, for example 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 (Ko et al. 2010). Besides physiological information, the sensors also collect environment and logistics data (e.g. patients' locations, equipment locations) needed for detection, diagnosis and treatment of medical symptoms, but also for the management of the clinical workflow in which these activities occur. An important consequence of combining the different types of information provided by various sensors is the possibility of *context-awareness*.

Traditionally, environmental sensors such as RFID readers, video cameras, sound, pressure, temperature, luminosity and humidity sensors provide contextual information. However, besides sensing their environment, some embedded and implantable sensors are being increasingly used to trigger physiological- and other interventions (e.g. brain-controlled motor prosthetics, or preventing epileptic seizures). Hence, medical sensors today can be considered as systems that also host actuators in addition to transmitters and processing units (e.g. as shown in Fig. 1). Examples of medical sensor types affected by this evolution are thermometers, blood pressure and glucose monitors, electrocardiogram, photoplethysmogram, electroencephalography, imaging sensors, accelerometers, gyroscopes and Global Positioning System devices. Various types of actuators can be associated to the sensor nodes, such as device triggers, alarms, pacemakers, insulin pumps, etc.

Many emerging IoT applications have the potential to revolutionise healthcare IS-es, particularly in aspects of monitoring and prevention, clinical workflow efficiency and wide-scale clinical research. Thus, for example home-based real time health monitoring of people behaviour for particular demographics can significantly improve life quality (Patrick 2009). Health-related monitoring can be correlated with social and environmental context observations (e.g. exposure to environmental factors such as pollution) in order to build a broader and more integrated view of the situation and thus enabling more informed decisions and feedback.

Evolving healthcare IoT IS are increasingly complemented by IoT applications used in other domains. For example, smart homes with context-aware infrared sensors, computers, biosensors and video cameras, emergency communication, control of home appliances and acoustic tracking (Liao et al. 2005) are environments which can be used for monitoring people behaviour. More specific application examples are assisting devices for the visually impaired, such as way-finding and walking navigation (Dabiri et al. 2008) and sensors integrated into clothing that detects biochemical changes in sweat, which may indicate health-related problems in real-time (Morris et al. 2009). High resolution monitoring of movement and activity levels can be used for the purpose of recovering patient's motor coordination (e.g. used to measure the effect of treatments) or for continuous monitoring of cognitive disorders, such as Alzheimer's and Parkinson's. Such systems can already collect user activity data to characterize certain patterns, such as walking, sitting or typing (Ganti et al. 2006), can detect certain postures or predict falls even before incident occurs (Nyan et al. 2008).

Real-time patient monitoring systems are implemented for the purpose of early detection of clinical emergency. They are used to continuously track the vital signs of the patient, e.g. pulse oximetry, respiration rate, temperature, heart rate, heart rate variability, arterial blood pressure, skin temperature and conductance, blood alcohol concentration, etc. Besides the vital signs information, other typical components of the response to a clinical emergency are the patient's electronic health record (EHR) and assignment of the respondent (doctor), based on physical location information (Rastegari et al. 2011); these location and proximity sensing technologies can have a significant effect in improving the workflow efficiency in hospitals (Fry and Lenert 2005). Often, physical location of a person or an object is a very important factor for a prompt, reliable and effective response (for example, identifying the nearest suitable doctor in case of a critical condition of a patient). In another example, IoT technologies can be used to assist emergency response in disaster events by enabling automatic patient triage and at the same time tracking the health status of the first respondents (Gao et al. 2008).

The synthesis of data acquired from a large number of sensors deployed in the field can also be used to track the spread of chronic diseases and pandemics (Hanjagi et al. 2007) or to facilitate large scale field studies of human behaviour (e.g. the use of energy during specific activities and the variance across a population of subjects (Patrick 2009)). This type of applications combine body-area wireless sensor networks with sensor-equipped smart phones and cloud-based data storage and processing services, leading to a new paradigm of population-scale medical research studies.

Currently, there are notable shortcomings affecting the development of pervasive healthcare IS, such as limited network capacity, processing and memory constraints, energy consumption and system reliability, typically resulting in inconsistent quality of service. Data accuracy and trustworthiness, manifested through erratic source integrity and availability, are another two important issues. In respect to source integrity, Ko et al. (2009) found that the rate of packet losses for radios based on IEEE 802.15.4 standard is much higher in hospitals than in other indoor environments. The root cause of this problem appears to be the sizeable concentration of devices affected by a high rate of interference such as Wi-Fi networks, Bluetooth devices, cordless phones and similar devices. The source availability perspective brings forth the data delivery latency issue, which is most likely to affect systems with actuators, especially when urgent action is required. Pervasive systems facilitate continuous tracking and monitoring; however, currently they are typically *soft* real-time systems, where some latency is allowed (Shin and Ramanathan, 1994).

While such shortcomings must be resolved to enable the evolution of the IoT, they are mostly of a technological nature and thus likely to be resolved by the continuous advances in information and communication technology. The main challenge to IoT progress appears to lie within the currently accepted interoperability concept itself, as further described.

INTEROPERABILITY IN THE WORLD OF INTERNET OF THINGS

Ubiquitous computing can provide a more natural interaction of the humans with information and services through embedding specific artefacts into their environment as unobtrusively as possible (Estrin et al. 2002). An important aspect in this context is that the devices that interact with humans and among themselves must be aware of the context; the emergence of pervasive internet connectivity makes this possible through the highly anticipated IoT paradigm.

One of the greatest challenges for the IoT is enabling an increasingly heterogeneous set of devices to exchange relevant information and thus interoperate and cooperate. ISO/IEC 2382 (2014) (vocabulary for information technology) defines interoperability as "the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units". In turn, IEEE offers a broader definition of interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" (IEEE 1990). ISO14258 (2005) defines three main types of interoperability: 'integration' (total interoperability), 'federalisation' (minimal interoperability, hence mere compatibility) and 'unified', where the ontology is negotiated in advance to provide semantic interoperability.

The IoT requirements raise key issues with such definitions of interoperability, which assume reciprocal awareness of the actors and their agreement on behaviours for a given interaction, derived from a pre-defined motivation to interoperate. Unfortunately however, such assumptions cannot hold in future ad-hoc communication and interoperation of the anticipated vast variety of systems participating in ubiquitous computing. Thus, concepts such as sharing and social context assumed by the current collaboration paradigm may become *obstacles* to interoperability, due to the reliance on previous agreements between the interoperating systems; as the number of connected devices and their technological diversity grows, it would become exponentially difficult to reach such pre-agreements.

The current interoperability approach also inevitably leads to IS application silos, with fragmented architectures, incoherent unifying concepts and hence, reduced reuse potential. This fragmentation, which occurs due to the inherently restricted domain of interest of the different architectures, is a barrier to context awareness, leading to potentially biased observations and flawed actions. For example, the diastolic blood pressure increases significantly at lower ambient temperatures; as such, the absence of ambient temperature information in measuring diastolic blood pressure may lead to false conclusions and potentially trigger the wrong response.

For the above reasons, it is highly likely that in the near future, the 'things' (irrespective of complexity, i.e. whether information systems-of-systems, agents, or elementary devices, etc.) belonging to the IoT will be required to accept ad-hoc signals and requests from other devices, interpret their meaning and act accordingly. Referring to the previous example, while the room temperature is not a feature of interest for a typical blood pressure measuring machine, an IoT-enabled device of this type will observe and perceive temperature information by interacting with surrounding temperature sensors (whatever and wherever these sensors may be) during the continuous monitoring process and take it into account in the processing.

The control theory can be used to demonstrate the complexity of the ubiquitous environments. Thus, any 'thing' in the IoT can be considered a closed-loop, or feedback control system. For example, to implement a control system for a process (e.g. patient triage workflow), a controller (e.g. manager/s assisted by expert system/s) must collect data from- and transmit appropriate feedback to this process. The control is carried out by actuators (e.g. supervisors), which apply continuous and discrete parameters (e.g. policies) to the process, based on processed information gathered from the sensors (e.g. dashboard/s). The typical objective of process control is to maintain a stable operation (e.g. within the agreed key performance indicators), by forecasting and issuing solutions for appropriate corrective actions whenever necessary.

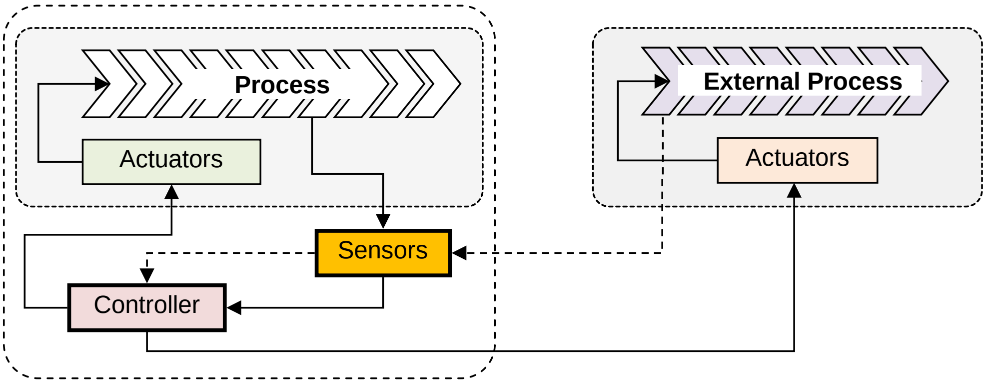

Fig. 1. Extended control system

In the interoperable world of ubiquitous computing, the roles of the sensor and controller would not be exclusive to the process to which they are initially committed. Thus, sensors can measure continuous and discrete variables for other processes in their environment, while controlling agents interpret these variables and may decide on corresponding actions on these processes (see Fig.1). Thus, new roles (in fact, new processes, such as e.g. assignment of first respondents) may be mandated to the sensor and controller components of the control system. However, this is only a functional boundary as the control system components remain within their physical unit. Hence, a new requirement for the sensors and controllers is that they must be able to receive and process new types of signals (data) - possibly unrelated to the process they were initially committed to.

In order for this to become possible, sensors and controllers need to be capable to interpret these new signals, *infer* their meanings, decide on the action/s to carry out based on these meanings and potentially perform these actions. Generally, this capability would be required from all participants aspiring to interoperate in the new environment of ubiquitous systems, irrespective of their complexity (IS and IS subsystems, agents, devices, elementary sensors etc.).

To illustrate this requirement at an elementary healthcare IS level, consider a 'future IoT' scenario where a person with an embedded blood pressure sensor BP is moving (or being moved) between hospitals or between the departments of a hospital (see Fig.2). This sensor is capable to sense and perceive *any* message received from its environment.

In the environment of BP, there are other sensors, observing the environment and continuously transmitting observed data. For example, a temperature sensor T is sending messages M_T, containing air temperature information. This message is sensed and observed by BP (O_{BPT}). At the same time, the blood pressure sensor BP is also collecting its own observations (O_{BPBP}). As previously mentioned, the perception of blood pressure increase without consideration of the ambient temperature) can lead to false conclusions. In this case, BP avoids this issue by creating a percept P_{BP} based on both the external (O_{BPT}) and its own (O_{BPBP}) observations. Upon perceiving P_{BP}, BP is capable to take an *appropriate* course of action, for example make a decision D_{BPT} to send an SMS to a physician. Let us assume that BP articulates and sends out a message A_{BP}, containing a request to send an SMS with designated content and recipient. This message is observed, interpreted and acted upon appropriately by e.g. a broadcasting device BD, with SMS sending capability.

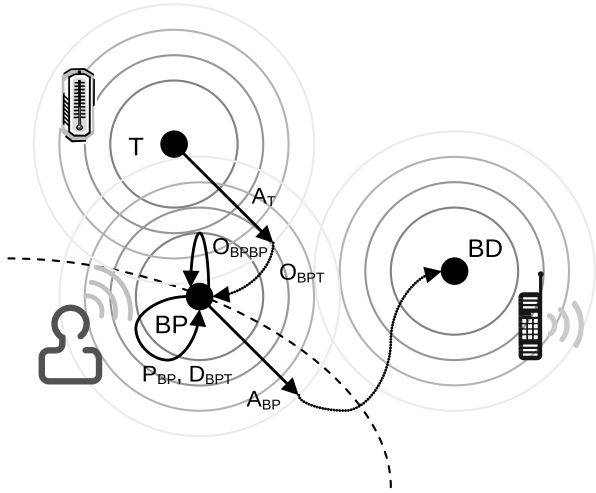

Fig. 2. Scenario of future IoT

The above scenario illustrates the tremendous potential benefits of the future pervasive healthcare. Namely, the capability of one system to exhibit *interoperability as a property* (IaaP) implies the 'de-verticalisation' of the existing IoT solutions and hence, the opportunity to combine access to various devices belonging to specific vertical architectures, achieving on-demand, real-time construction of the virtual ecosystems required to promptly address specific requirements presented by various and often unforeseen medical events. This would significantly reduce the costs of the healthcare and importantly, also decrease the response time which is typically a key factor in saving lives.

ENABLING FACTORS FOR INTEROPERABILITY AS A PROPERTY (IAAP)

In the example above, BP is able to observe, perceive, understand and decide to act based on information from heterogeneous sources which are not committed to pre-agreements on awareness, motivation and behaviour – thus, in essence displaying IaaP. The question arises: what is needed to make the above scenario possible, i.e. what are the enabling factors for IaaP? Based on the scenario in Fig. 2, one can infer a set of basic requirements for the autonomous, intelligent, purposeful and social behaviour of a 'thing' in an IoT-specific interoperable environment (such as e.g. a WSN used to support a pervasive healthcare IS).

To start with, an IaaP-enabled 'thing' needs to display self- and environmental *awareness*. Self-awareness is related to the capability of the 'thing' to sense a phenomenon or an event within itself. For example, WSN nodes need to be aware of their available energy levels. Environmental awareness is related to the capability of the 'thing' to sense a phenomenon or an event from its environment, extended by the capability to receive a message from its environment. Currently, the awareness of nodes (e.g. in WSNs) is functional in its nature and thus, restricted; namely, the sensor is aware only of the environmental features matching its pre-determined interest and/or can only receive a message of a known format (hence, being self-aware).

An IaaP-enabled 'thing' also needs to display *perceptivity*, i.e. the capability to assign a *meaning* to an observation. Such observations can occur within the thing itself or from its environment and they are typically multi-modal (involving e.g. temperature, light, sound, etc.) and possibly multi-dimensional (e.g. they may be time- and location dependent). Perceptivity facilitates *universal* (vs. mere functional, see above) awareness, enabling 'things' to observe based on arbitrary stimuli and interpret these observations, transforming them into a meaningful *percept*. Subsequently, based on this perception, the 'thing' should be able to decide on an appropriate action.

The decision to act based on a perception must be the result of a cognitive process, consisting of identification, analysis and synthesis of the possible actions to perform in response to the understood observation (i.e., the percept). Therefore, IaaP-enabled 'things' must also feature *intelligence* - encompassing assertion, storing and acquisition of the behaviour patterns, based on post-agreements in regards to the purposefulness of the performed actions. It must be noted that here, the term 'intelligence' does not directly refer to inference in terms of the mostly-used Description Logic-based models. Instead, the IaaP-enabled 'things' must take into account that the increased complexity of IoT design will bring about vagueness and uncertainty, which will ultimately pose the need to consider the progressive abandonment of the deterministic approach in business applications. In fact, the IoT 'things' will need to exhibit computational flexibility by effectively combining deterministic and non-deterministic reasoning, such as e.g. described by Costa and Laskey (2006) who formally defined a probabilistic ontology based on a Bayesian Network, and developed the OWL extension (PR-OWL) consistent with the former definition.

Another required attribute of the 'thing' would be *extroversion*, related to the willingness and capability of the thing to articulate its above actions. This attribute demonstrates the concern of the 'thing' about its physical and social environment while also reflecting *curiosity* as the capability to articulate the request for additional information needed for a more complete reasoning during perception and decision.

THE IAAP IMPACT ON ACHIEVING PERVASIVE HEALTHCARE INFORMATION SYSTEMS

Presuming that the 'things' in the healthcare IS domain will meet the requirements of the IaaP, how would this assist healthcare providers in meeting the significant challenges that lay ahead? The answer to this question is attempted using organisational and technical perspectives, taking each IaaP enabling factor into account.

When dealing with complex systems such as healthcare organisations, interoperability has many facets, as described in several mainstream interoperability frameworks. However, the combined framework analysis performed by Noran and Panetto (2013) and the semantic information systems analysis performed by Zdravkovic et al. (2013) has shown that even at this level, semantic interoperability still prevails as the most important and difficult to solve aspect. This encourages the extension of the proposed IaaP concept to healthcare providers IS, at all levels (i.e. from major, down to elementary IS components) to and in all aspects (software and hardware, humans and machines, etc.).

To start with, extending the IaaP concept to the entire organisation would assist healthcare providers in gaining *agility*. An agile organisation would be able to interoperate to a larger degree without having to become integrated in a specific negotiated framework or system / of systems (see Fig. 3).

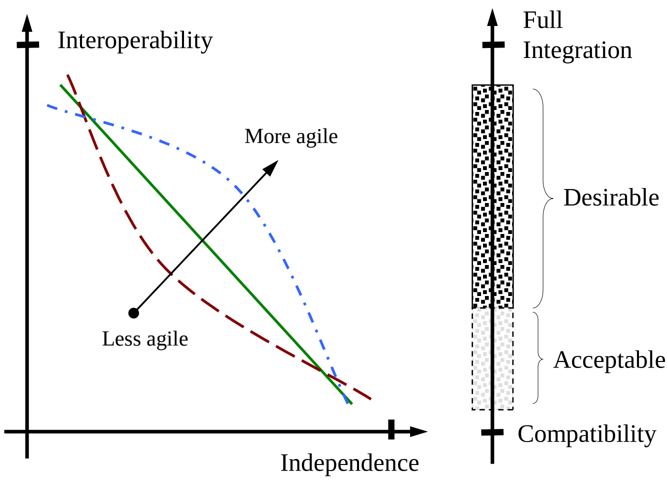

Fig. 3 Interoperability vs. independence (based on (Panetto 2007; Noran and Bernus 2011))

Preserving organisation independence and resilience would prove crucial in emergency situations where task force partners may unexpectedly fail, with the rest of the team having to provide the failed partner's IS functions or promptly find a replacement (Noran and Bernus 2011). Taking over another organisation's IS tasks would require prompt interoperation in areas not previously negotiated and thus facilitated by displaying the universal awareness and perceptivity brought about by IaaP.

Healthcare providers and their IS are highly heterogeneous and hierarchical, posing a variety of internal and external interoperability barriers, as described by Noran and Panetto (2013). The IaaP paradigm can be used to overcome or at least relieve some effects of these barriers. Thus, internal information sharing, heavily affected by hierarchy and culture that encourages 'silos of information', could be greatly improved by the awareness and perceptivity provided by IaaP to all IS components (importantly, including humans). Externally, by displaying IaaP, healthcare providers could significantly reduce the time required to set up emergency response task forces for disaster management and also to take part in 'healthcare management virtual organisations' (Noran 2013b) for long term problems such as increased healthcare services demand due to population aging and the need for care at home for the aged, disabled, chronically ill etc.

The beneficial effects that can arise by embracing the IaaP approach are further explained below in relation to each of the previously defined IaaP enabling factors.

Awareness. True and efficient collaboration is not possible unless the organisational cultures, processes and resources of the participants possess the required interoperability preparedness (Kapucu et al. 2010). Universal environmental awareness would greatly enhance the healthcare provider's preparedness for cooperation, both inside and outside its own boundaries. Thus, on the internal level medical safety and collaboration between various departments of healthcare providers would be dramatically improved as monitoring devices would keep track of the inpatients and be able to interoperate across the healthcare provider's departments. This would replace the current lack of IS interoperability (some of which still involve manual data transfer with paper-based stages) with ubiquitous awareness and data sharing for every patient. On the external level, the healthcare providers would be able to seamlessly exchange information about shared patients and also monitor outpatients' recovery progress in real time, irrespective of location and taking into account all relevant ambient factors. Therefore, the internal and external IaaP-based IS cooperation enhancement would greatly decrease the risk of medical errors and fatalities and enhance patient welfare.

Perceptivity and *Intelligence*. All healthcare organisations implement some kind of knowledge management IS or business intelligence; however, typically they only cover the upper and possibly middle management levels. In the IaaP scenario, such a knowledge management system would evolve into an expert system extending throughout the organisation, from top management to the elementary real-time response units, enabled by a pervasive, ubiquitous computing framework integrating intelligent sensors, controllers and actuators. Such a knowledge management system will use various internal and external models as so-called perceptual sets, connected theories representing the knowledge on the different domains and behavioural specifications (e.g. processes and / or tasks). Being inherently inclusive and open, the pervasive healthcare IS and their components will be capable to access these models on demand, combine their concepts with known specifications in real time and hence, construct the high-fidelity percepts required to make appropriate decisions. Thus, the healthcare provider would in fact become a learning organisation that constantly improves and adjusts its response to external challenges, while becoming more flexible and agile.

Extroversion. The healthcare IS and components should be able (and mandated) to articulate, justify and explain the decisions made. In addition to facilitating e.g. fault finding and continuous improvement, the social effect of the resulting extrovert healthcare system, manifested by transparency towards patients, other providers and general public, would be tremendously positive; especially in large scale healthcare incidents, trust and communication are paramount to achieve an effective population response and minimising negative effects (e.g. panic, mistrust, etc.).

The IaaP paradigm and its enabling factors would also benefit technical aspects of pervasive healthcare IS. Thus, the reliability issue present due to the extreme environmental conditions that affect medical sensors' communication is typically addressed nowadays only by technical approaches, such as redundancy (Chipara et al. 2010). The IaaP concept reduces the reliability problem to ensuring completeness and correctness of reasoning during the perception process; hence, reliability can be addressed by perceptual sets (typically employing various models and meta-models) used by the things to perceive the observations.

A similar approach can be used to resolve potential privacy and security problems. Instead of using various conventional and non-conventional authentication schemes, the messages and signals emitted by the healthcare IS 'things' would include formal descriptions of the privacy and security policies. Such policies would then become part of the perceptual sets by providing additional context for decision-making in relation to potential consequent action.

Computing complexity, capacity and the implicit energy consumption issues (which are paramount e.g. for WSNs to be used in pervasive healthcare IS) are also addressed by this approach. Although the concept of IaaP potentially implies more traffic between the 'things' within the IoT environment, the apparent increase would be compensated by the intelligent processing capability. For example, in multi-hop WSNs, perceiving raw sensor data, interpreting it and transmitting the resulting meaningful percept (or acting upon it) as opposed to simply passing this raw data can significantly reduce the volume of communication between the sensor nodes and the gateways, or the processing components. Thus, allocating a processing capability to 'things' can in fact reduce the number of components and the amount of traffic. Computational flexibility, as an inherent property of the future IoT devices, will also positively affect energy consumption, by dynamically and automatically choosing energy-efficient inference strategies, while combining deterministic and non-deterministic reasoning.

Sample Application Domain: Orthopaedic Implants

The medical devices industry is a key target for the research and demonstration of the proposed concepts. Hence, in this paper, we refer to the domain of orthopaedic implants, which is currently characterized by a lack of effective customised solutions and hence, by a relatively large probability of co-morbidities (such as e.g. infections) which trigger extended recovery periods, loss of wages, increased treatment costs, etc.

For the above reasons, the scientific community is proposing the development of smart, sensor-embedded orthopaedic implants (Morgan et al. 2011), typically powered by piezoelectric ceramics (Platt et al. 2005), in order to determine patient recovery from orthopaedic surgery where the function of the bone is partially transferred to the implant. Implantable sensors have been used in orthopaedic research for some time; however, they have now evolved to extremely small wireless passive devices, thus requiring very little (if any) modification to the implant. They are an alternative for the conventional diagnostics which use X-Rays or MRIs which are considered expensive, time consuming and sometimes even unreliable.

Wachs et al. (2013) developed the prototypes of implantable sensors that can measure force, torque, load (e.g. load sharing between the bone and implant), strain, motion (e.g. loosening of bone-implant joint or implant elastic deformations), pH, temperature, and pressure. These sensors, together with the associated processing and reporting capabilities form a closed system considered as self-aware. The proposed *environmental* awareness would facilitate more accurate conclusions, such as for example by considering the effect of the external air temperature, humidity, chemical composition, etc. Moreover, it would also enable extended conclusions, e.g. related to the effect of the daily routine and activities of the patient on the measured parameters. Here, the proposed *intelligence* would enable to identify, assert and store the logical correspondences between two completely unrelated models – of the human behaviour and of the loads system in a bone-implant joint.

There are calls for- and research towards active, smart implants (Parvizi et al. 2007) that can facilitate a prompt automatic medical response in specific circumstances (Antoci et al. 2008). Implantable nano-sensors (Webster 2011) have been proposed to help determining if bone cells, bacteria or inflammatory cells are attached to an implant, based on their different conductivities. A smart, active IaaP-enabled implant device could, based on the information observed by such nano-sensors and using its intelligent reasoning feature, decide to activate the feedback loop (e.g. triggering the release of an antibiotic or anti-inflammatory agent). The device would be able to articulate and explain its response to the perceived information observed by the conductivity sensor, thus also displaying extroversion.

CONCLUSIONS AND FURTHER WORK

The current meaning of the interoperability concept is being challenged by new technologies and paradigms. An evaluation of the current healthcare challenges demanding agility and pervasiveness has been followed by a concise review of the ubiquitous computing used in healthcare. Subsequently, the paper has pointed to the imminent increase in internal and external IS collaboration problems caused by the use of the legacy interoperability concept in the context of rapidly increasing number of devices ('things') that will populate a 'future IoT'. A possible solution has then been proposed, describing interoperability as a property of a single IS (or IS component), rather than in connection to other pre-committed systems. Next, the paper has attempted to define the factors that would enable the evolution of interoperability from a typical set of agreements shared between interoperating parties, to a property owned by each 'thing' populating the world of the future IoT. The paper has investigated the application of this concept at small and large scale and the implications of achieving interoperability as a property on the healthcare providers and there IS-es.

The IaaP concept applied to the healthcare domain as shown above assists with ongoing efforts to formalize the biomedical domain and clinical systems data exchange and communication. In addition, IaaP has the potential to boost current work in formalizing EHR standards, such as HL7 (Health Level 7) and DICOM (Digital Imaging and Communications in Medicine) and it is also expected to positively affect existing methodologies and initiatives for healthcare integration such as Integrating the Healthcare Enterprise (IHE) (Vegoda 2002).

Further work is required to test and refine the IaaP concept and to address several outstanding issues. Further investigation is needed in order to ascertain if the current set of IaaP enabling factors is complete, also in view of previous work in multi-agent area. The applicability and impact of IaaP on cultural interoperability (Whitman and Panetto, 2006) and trust, aspects specific to the essential human component of the healthcare IS, must be further clarified. Furthermore, the influence of the life cycle phases of an IS (or IS component) on its own and others' capability to display IaaP must also be investigated.

COPYRIGHT

REFERENCES

Antoci, V., Adams, CS., & Freeman, T. (2008). Novel implant design with covalently-linked antibiotics inhibits periprosthetic infection. Paper presented at the *American Academy of Orthopaedic Surgeon 75th Annual Meeting*, San Francisco.

Costa, P.C.G., & Laskey, K.B. (2006). PR-OWL: A Framework for Probabilistic Ontologies Proceedings of the 2006 conference on Formal Ontology in Information Systems: *Proceedings of the 4th International Conference Formal Ontology in Information Systems (FOIS 2006)* (pp. 237-249). Amsterdam: IOS Press.

Chipara, O., Lu, C., Bailey, T.C., Roman, G.C. (2010) Reliable clinical monitoring using wireless sensor networks: experiences in a step-down hospital unit. In: *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, pp.155-168, ACM New York, NY, USA

Dabiri, F., Vahdatpour, A., Noshadi, H., Hagopian, H., Sarrafzadeh, M. (2008) Ubiquitous personal assistive system for neuropathy. In *Proceedings of the 2nd International Workshop on Systems and Networking Support for Health Care and Assisted Living Environments*. Article No. 17. ACM New York, NY, USA

Estrin, D., Culler, D., Pister, K., Sukhatme, G. (2002). Connecting the Physical World with Pervasive Networks. *IEEE Pervasive Computing*. Vol.1, Issue 1, pp 59-69

Fry, E.A., Lenert, L.A. (2005) MASCAL: RFID tracking of patients, staff and equipment to enhance hospital response to mass casualty events. In: *AMIA Annual Symposium Procs. Archive*. Vol.2005, pp.261-265.

Ganti, R.K., Jayachandran, P., Abdelzaher, T.F., Stankovic, J.A. (2006) SATIRE: A software architecture for smart AtTIRE. In: *Proceedings of the 4th International Conference on Mobile systems, applications and services*. pp. 110-123. ACM New York, NY, USA

Gao, T., Pesto, C., Selavo, L., Chen, Y., Ko, J., Lim, J.H., Terzis, A., Watt, A., Jeng, J., Chen, B., Lorincz, K., Welsh, M. (2008) Wireless medical sensor networks in emergency response: Implementation and pilot results. In *Proceedings of IEEE Conference on Technologies for Homeland Security*. pp.187 – 192

Hanjagi, A., Srihari, P., Rayamane, A.S. (2007) A public healthcare information system using GIS and GPS: A case study of Shiggaon. *GIS for Health and the Environment: Lecture Notes in Geoinformation and Cartography*. Vol.2007, pp.243-255. Springer Berlin Heidelberg

IEEE (1990). “IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries”, Institute of Electrical and Electronics Engineers

International Labour Organisation. (2009). Ageing societies: The benefits, and the costs, of living longer. Retrieved March, 2013, from http://www.ilo.org/global/publications/magazines-and-journals/world-of-work-magazine/articles/WCM_041965/lang--en/index.htm

International Standardisation Organisation (2005). ISO14258: Industrial Automation Systems, Concepts and Rules for Enterprise Models.

ISO/IEC (2014). ISO/IEC 2382: Information technology -Vocabulary. International Standards Organisation.

Kapucu, N., Arslan, T., Demiroz, F. (2010) Collaborative emergency management and national emergency management network. *Disaster Prevention and Management.* Vol.19, Issue 4, pp. 452-468

Ko, J., Gao, T., Terzis, A. (2009) Empirical study of medical sensor application in an urban emergency environment. In *Proceedings of the Fourth International Conference on Body Area Networks*. Article No. 10

Ko, J., Lu, C., Srivastava, M.B., Stankovic, J.A., Terzis, A., Welsh, M. (2010) Wireless sensor networks for healthcare. *Proceedings of the IEEE.* Vol.98, Issue 11

Liao, L., Fox, D., Kautz, H. (2005) Location-based activity recognition using relational Markov networks. In *Proceedings of the 19th international joint conference on Artificial intelligence*. pp 773-778. Morgan Kaufmann Publishers Inc. San Francisco, CA, USA

Morgan, C., Hall, H.T., Green, J.M., Flexner, G., Geltz, C.E. (2011) Orthopaedic implants with sensors. US Patent US8083741 B2

Morris, D., Coyle, S., Wu, Y., Lau, K.T., Wallace, G., Diamond, D. (2009) Bio-sensing textile based patch with integrated optical detection system for sweat monitoring. *Sensors and Actuators B: Chemical*. Vol.139, Issue 1, pp. 231-236

Nembhard, I.M., A.C. Edmondson (2006) Making It Safe: The Effects of Leader Inclusiveness and Professional Status on Psychological Safety and Improvement Efforts in Health Care Teams. *Journal of Organizational Behavior*. Vol.27, Issue 7, pp.941-966

Noran, O., Bernus, P. (2011). Effective Disaster Management: An Interoperability Perspective. *Lecture Notes in Computer Science*, 7046, 112-121.

Noran, O., Panetto, H. (2013) Modelling a Sustainable Cooperative Healthcare: An Interoperability-driven Approach. *Lecture Notes in Computer Science*. Vol.8186, pp.238-249

Noran, O. (2012) Towards Improving Information Systems Interoperability in Disaster Management. In *Building Sustainable Information Systems (Proceedings of the 2012 International Conference on Information Systems Development)* Springer Verlag: N.Y. pp. 123-134.

Noran, O. (2013a) A Multi-faceted Approach to Collaborative Health Information Systems. In *24th Australasian Conference on Information Systems (ACIS 2013)* Royal Melbourne Institute of Technology: Melbourne, Australia.

Noran, O. (2013b) Enhancing Collaborative Healthcare Synergy. *IFIP Advances in Information and Communication Technology*. Vol.408, pp.459-467

Nyan, M.N., Tay, F.E.H., Murugasu, E. (2008) A wearable system for pre-impact fall detection. *Journal of Biomechanics*. Vol.41, Issue 16, pp. 3475–3481

Parvizi, J., Antoci, V. , Hickok, N., & Shapiro, I. (2007). Selfprotective smart orthopedic implants. *Expert Rev Med Devices*, Vol. 4, Issue1, pp. 55-64.

Patrick, K. (2009) A tool for geospatial analysis of physical activity: Physical activity location measurement system (PALMS). *Medicine and Science in Sports and Exercise*. Vol.41, Issue 5.

Platt, S.R., Farritor, S., Garvin, K., Haider, H. (2005) The use of piezoelectric ceramics for electric power generation within orthopedic implants. IEEE/ASME Transactions on Mechatronics. 10(4)455-461

Rastegari, E., Rahmani, A., Setayeshi, S. (2011) Pervasive computing in healthcare systems. *World Academy of Science, Engineering and Technology*. 2011, Issue 59

Shin, K.G., Ramanathan, P. (1994) Real-time computing: a new discipline of computer science and engineering. *Proceedings of the IEEE*. Vol.82 , Issue 1

Vegoda, P. (2002). Introducing the IHE (Integrating the Healthcare Enterprise) concept. *J Healthc Inf Manag.*, Vol. 16, Issue 1, pp.22-24.

Wachs, R.A., Ellstein, D., Drazan, J., Healey, C.P., Uhl, R.L., Connor, K.A., Ledet, E.H. (2013) Elementary Implantable Force Sensor for Smart Orthopedic Implants. Advances in Biosensors and Bioelectronics, Vol. 2, Issue 4, pp.57-64

Waugh, W.L., Streib, G. (2006) Collaboration and Leadership for Effective Emergency Management. *Public Administration Review*. Vol.66/s1, pp. 131-140

Whitman, L., Panetto, H. (2006) The Missing Link: Culture and Language Barriers to Interoperability. *Annual Reviews in Control*, Vol.30, Issue 2, pp. 233-241

Webster T.J. (Ed), 2011. Nanotechnology Enabled In situ Sensors for Monitoring Health. Springer

Zdravković, M., Noran, O., & Trajanović, M. (2014). Towards Sensing Information Systems. In *Proceedings of 23rd International Conference on Information Systems (ISD2014)*. Berlin: Springer Verlag.

Zdravković, M., Panetto, M., Trajanović, M., & Aubry, A. (2013). Explication and semantic querying of enterprise information systems. *Knowledge and Information Systems*, DOI 10.1007/s10115-013-0650-x.