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Abstract. The advent of the future Internet-of-Things brings about increasing complexity and diversification of Enterprise Information Systems, which makes interoperability a critical requirement towards their scalability and sustainable development. This is especially evident in the disaster management area, which typically involves a highly heterogeneous set of institutions and organisations responsible for delivering emergency response services who often fail to rise up to the task, mainly due to a lack of proper collaboration. As the legacy consideration of the interoperability paradigm appears to fail in meeting these challenges, in this paper we define Interoperability as a Property (IaaP) of every ubiquitous system. In doing so, we use an anthropomorphic perspective to formally define IaaP's enabling attributes (namely, awareness, perceptivity, intelligence and extroversion), with the objective of taking initial steps towards a Theory of Interoperability of Everything (IoE). The identified concepts and their interrelations are illustrated by the presented IoE ontology.

Keywords: Internet-of-Things, Ubiquitous systems, Systems interoperability, Interoperability as Property, Disaster Management, Interoperability of Everything

1. Introduction

The rate and force of natural and man-made disasters, whether triggered or augmented by new strains of drug-resistant diseases, regional conflicts and climate change, appears to be on the rise. In this context, it is nowadays essential to effectively prevent, prepare for, promptly respond to and recover from catastrophic events. Governments worldwide tackle this challenge by creating specific policies, departments and 'disaster management' organisations (DMOs). Such organisations operate in a highly varied and complex historic, traditional, geographical, cultural and political environment, which results in their high organisational diversity.

Two of the most critical issues of disaster management are effective cooperation between all stakeholders and agile response to unpredictable events. Coping with large

scale catastrophic events typically demands resources and capabilities beyond those of any individual organisation; thus, the effective cooperation of DMOs at all necessary levels and addressing all relevant aspects is essential in order to minimize the loss of property and human life. An agile response to disasters can nowadays be facilitated by sensing and ubiquitous computing technologies, enabling early warnings and advanced processing of big data from disparate sources and leading to faster and better decision making. Therefore, the cooperation problem is typically focused on the issue of interoperability – of the various devices at low level and of the DMO IS' at higher level.
As computing systems become omnipresent with the rising uptake of the digital assets such as mobile devices, sensors, tags and other identifiable resources, the contemporary paradigm of systems interoperability turns out to be incomplete and insufficient, due to rapidly increasing complexity and related difficulties to achieve the necessary agreements. In fact, the legacy interoperability concept will work out only in the closed architectures of controlled scalability. In the 'open world', the perception of interoperability needs to evolve from the consideration of interoperating pairs of systems to the capability of an autonomous system to sense, interpret, understand and act upon arbitrary stimuli from its environment or the messages received from a potentially unknown sender, based on the known relevant or non-relevant, intrinsic and extrinsic properties (facts) of the world in its environment. In this sense, interoperability becomes in fact a property of the system.
In this paper, we discuss on the needed requirements for developing this property. Although the motivation for the presented work is drawn from the challenges of the disaster management processes, the discussion also aims at extending the general theories on the interoperability of systems. More specifically, the following research questions are asked: '*What is needed for a system to operate based on the message(s) of any arbitrary content, sent by other (potentially unknown) systems?'* and '*How would the DMO landscape benefit from the new concept of an inherently interoperable system'*. In order to answer these questions, the paper starts with a discussion of the key principles defining interoperability as a property (IaaP) of a single system in the context of DMO theory and practice, existing interoperability definitions and frameworks and the factors influencing ubiquitous computing technologies. Subsequently, it defines several IaaP enabling factors, based on a set of desirable system attributes. Finally, it proposes an IoE (Interoperability of Everything) ontology, which aims to formalise the concepts involved in defining IaaP.

2. Interoperability in Disaster Management

Merely mandating DMOs to 'cooperate' has proven insufficient; the lack of true collaboration has brought increased response times, confusion on the ground and sometimes even dispute as to who, where and when is in charge. Wilson et al [1]

reinforced this point by stating that collaboration does not automatically occur but rather must be "constructed, learned […]" and importantly, "[…] once established, protected" (ibid.). Coordination in crisis situations is also difficult due to infrastructures' incompatibilities and difficulty in filtering and validating the surge of information generated during disaster events. For example, inconsistencies in alert notice types and formats may confuse response teams and create a situation where the population is saturated with ambiguous and/or irrelevant messages [2]. This can lead to sub-optimal prevention and response by intended recipients and potential property and life loss. Efforts to standardise warning message protocols are still rather localised, with low take-up rates [3]. Various documents, inquiries, reviews and reports suggest that the root causes of current shortcomings could in fact be the inadequate preparedness and insufficient information quality and flow between the participants [4], owing mostly to infrastructure incompatibilities (originating in their inherent heterogeneity), lack of trust, organisational confusion and even due to perceptions of competition between the departments or institutions expected to cooperate. This emphasizes the fact that *true* collaboration is intricate and multifaceted, involving processes and resources but also organisational cultures of the participants [5].

A number of approaches have been studied for disaster management. To start with, the 'central command'-type approach, sometimes brought about by urgency and slow reaction of some participants [6] has proven to be unsustainable, as successful disaster management relies on a wide range of economic, social-psychological, and political community resources. The adoption of military-type network-enabled capabilities in disaster management [7] has also been found to have limited applicability due to potential over-reliance on failure-prone civilian communication infrastructures. The disaster management federalisation approach offered as an alternative to central command has also achieved sub-optimal results in the past [8]; however, this approach may be substantially improved by achieving cooperation *preparedness*. Unfortunately, poor aspect coverage, lack of commonly understood, integrated models and a missing mature cooperation paradigm have been major obstacles in achieving such preparedness. These issues can be mitigated by modelling and participatory design [9] aimed at integrating scientific but also administrative and political aspects into a whole-system disaster management approach [10].

Both typical approaches heavily depend on the use of information systems. When cooperation preparedness is considered, Emergency Management Information Systems (EMIS) are being used for resource management and preparation of contingency plans, but also for collecting data and reasoning about possible risk types and areas. In the response and recovery phases, EMIS support consistent execution of the contingency plans, cost calculation and reporting. The former implies that EMIS directly depend on Geographic Information Systems (GIS) that are being used for storing and managing relevant geo-data. Also, cooperative disaster response means that EMIS will have to collect data from the range of different sources, including the information systems of all stakeholders, mobile devices, sensors, etc.

The various aspects of and potential solutions to the collaboration issues identified above are addressed by the enterprise integration and networking communities, with special emphasis on enterprise interoperability as an essential enabler of cooperative disaster management.

2.1. Interoperability Aspects

Standards such as ISO14258 [11] and various interoperability frameworks such as the European Interoperability Framework (EIF) [12], IDEAS [13], ATHENA Interoperability Framework (AIF) [14] and the INTEROP Network of Excellence (NoE) Interoperability Framework [15] provide a plethora of viewpoints to be considered in an interoperability maturity assessment and enhancement.
In researching the above-mentioned standards and frameworks, we have found that they have overlapping and complementary areas; moreover, practice often requires considering a mix of these aspects for a given disaster management endeavour. Therefore, a combined model has been constructed for identifying the most relevant interoperability aspects [16][17] (see Fig. 1). As illustrated, the data and process aspects on the ATHENA-inspired 'concern' axis have been ranked as most stringent in DMO collaboration. This is because typically, the ability to extract and exchange a large amount of data (often featuring significant amounts of noise) from heterogeneous sources during disaster events is paramount to being aware of the conditions on the ground and avoiding potentially life-threatening situations for emergency response crews and for the population. Although prior agreements on data format and especially on its meaning are very beneficial, often this may not be possible, e.g. due to the large number of sensors and / or a high degree of heterogeneity.

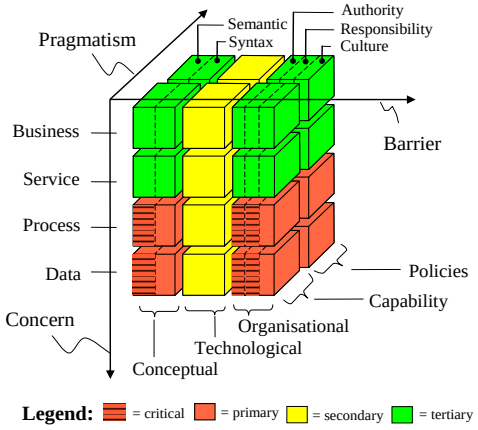

Fig. 1. An interpretation of the INTEROP NoE Interoperability Framework [15] enriched with concepts from ISO14258, EIF, IDEAS, ATHENA AIF, [21] and [53]

Organisational interoperability is an essential aspect in disaster management, as task force participants typically exhibit significant structure diversity. The issues identified by Chen [18] based on the EIF [12], namely responsibility, authority and type of organisation can all impact heavily on the functionality of a disaster management task force. Although it is highly beneficial to establish and agree upon the roles and hierarchy of all participants, as previously shown, in the disaster response phase some task force members and/or coordination may fail; therefore, the remaining participants must be able to dynamically reorganize (and if enlisting other participants, renegotiate) in order to continue responding to the emergency in the most efficient way.
DMO collaboration is inherently related to their systems' interoperability. For example, the information systems (IS) of these organisations (which are in fact their digital identities) implement the concerns of the interoperability framework by mandating capabilities related to business, services, processes and data, both on semantic and syntax levels. The IS also reflect interoperability policies, including authority and responsibility.

2.2. Interoperability Approach

ISO/IEC 2382 ('Information technology – Vocabulary') 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" [Def1]. In a more broad sense, IEEE defines interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [19] [Def2]. Thus, in this view, two 'interoperating' systems give reciprocal access to their resources.

When considering the ubiquitous computing aspects, we identify two main problems with the current definitions of interoperability. First, they assume necessary commitment and agreement of the participating actors on their behaviours for a given interaction, derived from the predefined motivation to interoperate. Second, they assume awareness of the existence of the system(s) they interoperate with. Both assumptions can no longer hold in the inherently ad-hoc interoperations of the large (and increasing) variety of systems typically present in ubiquitous computing. Even though the current collaboration culture assumes sharing and a social aspect, unfortunately these become obstacles for interoperability in the new context because they imply the previous agreements between the interoperating systems. Removing these agreements would mean that interoperability will become, in fact, purely semantic. To support that, we can refer to the often used definition of interoperability: "Interoperability is a property of a product or system, whose interfaces are completely understood, to work with other products or systems, present or future, without any restricted access or implementation" [Def3].

ISO14258 [11] establishes several ways to achieve interoperability: integrated (common format for all models), unified (common format at 'meta' level) and federated (participants negotiating ontology as they go to achieve a shared understanding of models). In the case of DMOs, neither full integration nor federalisation appeared to have achieved the desired results, mainly due to the organisational heterogeneity of DMOs and the impracticality to negotiate in real time during disaster response.The unified approach (presumably the most suited to this situation) requires only the ontology to be negotiated in advance. Unfortunately, notwithstanding significant advances in ontology integration [54, 55], currently the only sustainable solution to semantic disaster management interoperability appears to be when the DMOs 'spend time together' to agree on the *meanings* associated with the concepts used to exchange knowledge. A new solution, enabled by the emerging ubiquitous computing paradigm, may reside in the newly-defined IaaP concept [56, 57] which has the potential to resurrect the federated ('cooperation on the fly') approach; however this must be considered in the context of human-specific processes (e.g. negotiation, trust) which cannot be successfully rushed or left to be performed during project operation.

2.3. Interoperability in the Context of Internet of Things

The Internet of Things (IoT) [22] is defined as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication [23]. In IoT, the 'things' have unique identities, physical attributes, and virtual personalities. They are expected to become active participants in business, information and social processes where they can interact and communicate among themselves and with the environment by exchanging information 'sensed' from their near environment, while reacting to the real world events and even affecting it by triggering some actions. Intelligent interfaces facilitate interactions with these 'things' on the Internet, query and change their state and any information associated with them, while also taking into account security and privacy issues.

With the advent of IoT and implementing technologies (number of devices connected to Internet forecasted to grow to 50 billion by 2020 [24]), computing will become ubiquitous – *any device, location and format*. Ubiquitous computing aims to provide more natural interaction of humans with information and services, by embedding these into their environment as unobtrusively as possible [25]; thus, humans may not even be aware of the fact of it occurring in the background. Importantly, the devices that interact with humans and among themselves are to be local but also *universal* context.-aware.

IoT is mainly evolving from the current research on Wireless Sensor Networks (WSN), usually consisting of a set of 'nodes' (tens, hundreds, or even thousands of sensors), which acquire, store, transform and communicate data using wireless technologies [26]. These autonomous nodes are spatially distributed with aim to monitor physical or environmental conditions, such as temperature, sound, pressure, etc., to

cooperatively pass their data through the network to a main location, but also to enable a control of a sensor or associated device's activity.

While today, WSN are mostly used in military applications, environmental (indoor and outdoor) monitoring, logistics, healthcare applications and robotics [27], their use is also spreading into the emergency management domain. Thus, IoT technology can be used to enhance disaster management prevention, preparation, and response by WSN [28] - e.g. for providing emergency care in large disasters [29] using respondent assignment based on location information [30]. Note that, while typically the physical location of people or objects is a deciding factor for promptly taking the right decision, it often needs to be interpreted in the context of other information – such as environmental factors (temperature, air composition etc.). The synthesis of data acquired from the potentially large number of sensors is useful in disaster prevention by facilitating large scale field studies for example to track the spread of diseases [31]. Besides the specific applications for the specific types of events, the emergence of WSN also affected general methodological approaches in disaster management, by introducing the development of new protocols for rescue operation [32], distributed event detection [33], adaptive management of sensors [34], etc. WSN significantly increased the efficiency of the conventional tools for disaster monitoring, e.g. different uses of aerial sensor networks have been proposed for acquiring high quality and timely data on the disaster events [35]. The IoT paradigm can provide additional capabilities to the disaster monitoring networks [36][37], such as distributed processing capability, real-time identification, combining big sources of data with the observations, e.g. data from social networks [38] and others.

One of the greatest challenges for the IoT is about making different devices exchange the relevant information and consequently, making them interoperate. Current applications of the ubiquitous systems are typically based on the pre-agreement of the different devices to exchange information and to act upon this information. However, as the number of connected devices and their technological diversity grows, it will become increasingly difficult and time-consuming to work on reaching these pre-agreements.

More importantly, the current approach will inevitably lead to application silos, with fragmented architectures, incoherent unifying concepts, and hence, little reuse potential. Thus, it is highly likely that the 'things' of the future ubiquitous systems will be required to interpret ad-hoc signals and requests from other devices (including the *motivation* behind these signals) and act according to the interpreted motivation.

3. Interoperability as a Property of a Single System

Let us consider an IoT scenario where an emergency response crew with an embedded GPS sensor (GP) is deployed on the ground, moving between response areas in the conditions of a chain of catastrophic events - e.g. an earthquake triggering a toxic /

radioactive spill (see Fig. 2). The sensor GP is capable to sense and perceive any message received from its environment.

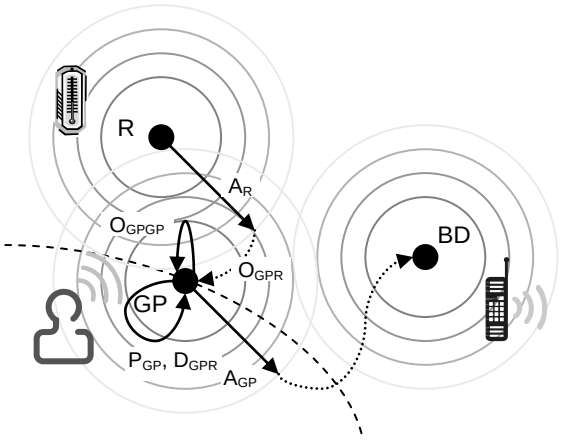

Fig. 2. IoT-enabled emergency response scenario

In the environment of GP there are other sensors (e.g. low power wireless sensor nodes within a network), observing the environment and continuously transmitting the observed data. For example, sensor R is continuously sending message A_R, containing the detected radioactive level. This message is sensed and observed (O_{GPR}) by GP. In the meantime, GP is continuously collecting its own observations (O_{GPGP}). Perception of the crew position, in the context of the radioactive level of the environment can lead to recognising a life-threatening situation for the crew. In this case GP is creating a percept P_{GP}, based on two observations, namely O_{GPR} and O_{GPGP}. Based on this perception, GP is capable to make a decision D_{GPR}, e.g. to send SMS to a command and control centre and/or other crews. Hence, GP articulates and sends out a message A_{GP}, with request to send SMS with designated content and recipient. Finally, there is a device BD (embedded in the crew in question, ground-based station or another crew, etc) with SMS broadcasting capability, which observes this message and acts further upon it.

The problem described above can be tackled through a specialisation of IoT for services (Internet of Services, IoS). However, IoS implies functional organization, i.e. defining BD's capability to send SMS messages in advance as a service, associated with required input requests by means of format, protocol to deliver, etc. Unfortunately, such requirements are pre-conditions to interoperate and hence, obstacles to IaaP. It is important to highlight that, in this case, the communicating entity (GP) is not aware of the existence of the receiving entity (BD), not to mention its capability to perform the required task. This is an extension of [Def1] definition of interoperability, which assumes no "knowledge of the unique characteristics of the interoperating systems".

As explicitly stated in [Def3], with the current consideration of the autonomous systems, the concept of interoperability must be evolved to represent the property of a *single* system. This property determines the capacity of a system (in a general sense) to adapt, respond, act internally or externally, etc. to specific circumstances. As referred in [Def3], this capability depends on the 'understanding of the interfaces'.

A social context is important in order to define IaaP purposefulness. Thus, in the vaguely defined context of IoT, interoperability would mean *properly* reacting to the utterances of others (assessed using a post-agreement on what a 'proper' reaction is). In other words, the ultimate test to see whether one system has reacted 'properly' may be to see how its environment responds to its reaction. The social context of the interoperation may be pre-determined, as some systems may expose their capabilities by using services, since these services actually define what kind of specific information can be exchanged between systems and how this information is articulated.

3.1. Interoperability as a Property: Enabling Attributes and Factors

When considering enabling factors for the above scenarios, one must first identify key attributes of the 'things' required for their interoperable behaviour and then investigate candidate technologies, methodologies and assets to achieve each of these attributes.

In an anthropomorphic consideration, the minimum requirements for an autonomous, intelligent, purposeful, social behaviour of a 'thing' in the interoperable environment, such as WSN, appear to be awareness, perceptivity, intelligence and extroversion.

In regards to *awareness*, we can distinguish between two main aspects: self-awareness and environmental awareness. *Self-awareness* is related to the capability of a 'thing' to sense a phenomenon or an event within itself. For example, WSN nodes need to be aware of the available energy levels. For example, the data communication policy of a node may differ from its acquisition policy (different frequency), due to energy issues. The decisions of adapting these policies to the current energy constraints could be made autonomously by the nodes and their behaviour may be adapted in time to optimize their lifetime, under the condition that this optimized behaviour is previously negotiated with other nodes. *Environmental awareness* is related to the capability of a 'thing' to sense a phenomenon or an event from its environment. We also extend this consideration by adding the simple capability to receive a message from its environment. The former is a core functionality of a node in WSN and hence, it will not be elaborated in detail. However, it is important to highlight that the awareness of the current nodes is functional in its nature and thus, restricted. Namely, the sensor is aware only of the environmental features of its (pre-determined) interest. A similar point can be made related to the capability of a 'thing' to receive a message (of a known format). Hence, we can distinguish between *functional* and *universal* environmental awareness.

Perceptivity is a property of a 'thing', related to its capability to assign a meaning to the observation from its environment or from within itself. While awareness and self-awareness are properties that have been already achieved by WSN nodes, but only in the

restricted, strictly functional scope, perceptivity goes one step further. It enables the 'things' to observe based on the arbitrary stimuli and consequently to perceive these observations – namely, to transform the physical observation to a meaningful *percept*. These observations are typically multi-modal (e.g. temperature, light, sound, etc.) and diverse in many dimensions (e.g. they are time and location dependent).

Based on the above-mentioned percept, a 'thing' 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 (namely, a percept). *Intelligence*, as an attribute of the interoperability property also encompasses assertion, storing and acquisition of the behaviour patterns, based on the post-agreements on the purposefulness of the performed actions.

The last identified attribute of the 'thing', extroversion, is related to its willingness and capability to articulate the actions taken. It also demonstrates the thing's concern about its physical and social environment.

The remainder of this section will provide a more detailed elaboration including an overview of the existing candidate technologies, methodologies and assets that might be used to enable the above attributes and thus facilitate IaaP of ubiquitous systems. A detailed discussion on enabling extroversion is not provided, since articulation of one message is considered as a trivial problem once the system is capable to perceive it.

Enabling Awareness

The behaviour related to the self-awareness of the nodes can be facilitated by using sensor ontologies. Several ontologies have been developed to represent sensors and their behaviour, since 2004 [39], and analysed in the extensive review of the W3C Semantic Sensor Network Incubator Group [40], which was used for the purpose of developing W3C Semantic Sensor Network (SSN) Ontology.

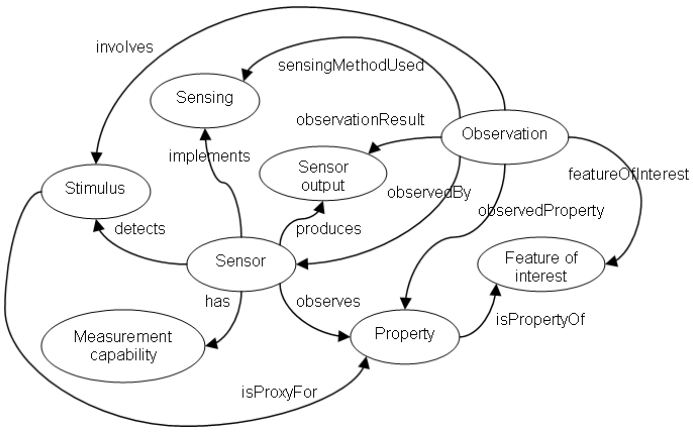

Fig. 3. Skeleton of the Semantic Sensor Network ontology

The SSN Ontology [41] is a formal OWL DL ontology for modelling sensor devices (and their capabilities), systems and processes. It is universal in the sense that it does not assume a physical implementation of a sensor; thus, it can be used to describe the process of sensing by the WSN nodes. SSN unfolds around the central pattern relating what the sensor observes to what it detects. While the latter is determined on basis of its capability (namely accuracy, latency, frequency, resolution, etc.) and a stimulus, the former is related to the concepts of features of interest, their properties, observation result and sampling time, etc. The skeleton of SSN ontology is illustrated in Fig. 3.

Stimuli are detectable changes in the environment that trigger the sensors (or a decision of a sensor to perform observations). They are related to the observable properties and hence, to the features of interest. The same types of stimulus can trigger different kinds of sensors and can be used to reason about different properties.

Sensors perform observations by transforming incoming stimuli to other representations. They are related to the procedure of sensing – i.e. how a sensor should be conceived and deployed in order to measure a certain observable property. Observations are typically seen as elements of an observation procedure.

Properties are qualities of the feature of interest (entities of the real world that are target of sensing) that can be observed via stimuli by the sensors.

Sensor ontology is a useful asset for directly facilitating self-awareness. Furthermore, it can be extended to enable processing of pre-determined, expected observations and drawing explicit conclusions, thus facilitating functional environmental awareness. For example, a reference extension relevant for the work presented in this paper are IoT-enabled business services that collect and process sensor data within a rescue environment [42].

Enabling Perceptivity

Cognitive psychology considers perception as the organization, identification, and interpretation of sensory information carried out with the objective to represent and understand the environment [43]. Perceptivity is tightly related to the awareness attribute in the sense that constructing the meaning from observation data is a pre-condition for understanding the context in which some interoperations or communications occur. In other words, the known meaning of the sensor data or data pattern contributes to its communication context awareness, or more specifically, its situational awareness. When considering the awareness capabilities, one can distinguish between perceptivity related to observing sensor data and perceptivity related to assigning a meaning to an incoming message. Consequently, one can classify *observational* and *communicative* perceptivity. While observational perceptivity is related to computing a percept on basis of a raw sensor data, communicative perceptivity is considered as its extension, meaning that sensed data is in fact a message articulated by other system in that case. A 'thing' that exhibits both capabilities may process the sensor data and messages in a combined way.

Kno.e.sis (Ohio Center of Excellence in Knowledge-enabled Computing) and the University of Surrey, UK developed and implemented a methodology [44] to identify patterns from sensor data, by using Symbolic Aggregate Approximation (SAX). These patterns are then translated into abstractions with an abductive logic framework called Parsimonious Covering Theory (PCT) [45], approximated by using OWL. The abstractions are directly, or by using reasoning mechanisms, related to an event or a phenomenon. PCT uses domain-specific knowledge to determine the best explanation for a set of observations, namely to link the patterns to semantic descriptions of different relevant thematic, spatial and temporal features. Subsequently, Henson et al developed IntellegO ontology of perception [46] with the objective to provide formal semantics of a machine perception. IntellegO was created based on the principles of Neisser's Perception Cycle [47], according to which a perception is considered as a cyclic process, in which the observation of the environment, followed by the creation of the initial percepts, is often affected by the process that attention is directed to for further exploration (in order to get more stimuli required to construct the final percept). In this process, humans generate, validate and consequently reduce the hypotheses that explain their observations. According to IntellegO, based on the observed qualities of the inherent properties of the observed object, a subject creates a number of percepts as parts of the so-called *perceptual theory*. Then, in order to clarify which qualities enable the reduction of the perceptual-theory, the following types are classified: expected, unknown, extraneous and discriminating. Hence, the specific goal of the perception cycle is to generate a minimum perceptual theory for a given set of percepts. These percepts may not come only from the features of interest but also from the general environment of a 'thing', to which some questions may need to be asked. Hence, perceptivity cannot be addressed independently of extroversion, which is used to articulate these questions.

Current work on defining the models in the IoT domain is mostly focused on the resources description for management. However, the aspect of accessing and utilizing information generated in IoT is equally important as an enabler of the aforementioned descriptions. This aspect is addressed by Wang et al. [48], who developed a comprehensive ontology for knowledge representation in the IoT. This ontology extends the current work on representation of resources in IoT by introducing service modelling, Quality of Service (QoS) and Quality of Information (QoI) aspects.
The trend of service-enablement of 'things' entices the consideration of their capability to perceive interfaces (services), rather than just data and / or information. Although this is somewhat out of the scope of the initial research question, it must be taken into account, as the services are credible elements of the 'things' environment. Perceiving service interfaces in IoT is tightly related to their discovery. Guinard et al. [49] proposed an architecture for dynamically querying, selecting and using services running on physical devices. This architecture can be particularly useful for finding the relevant observation in a specific context. With regard to this, it is important to take into account the specification of Sensor Observation Service (SOS) web service [50] accomplished by the Open Geospatial Consortium (OGC). Finally, Pschorr et al [51] have shown that publishing sensor data as Open Linked Data complementing the use of sensor discovery service can enable the discovery and accessing the sensors positioned near named locations of interest.

Enabling Intelligence

In a broad sense, intelligence as an attribute of the 'thing' is related to its processing or computational capability. The processing unit (also associated with small storage unit) is already embedded in the current architecture of nodes in WSNs and its key objective is to reduce energy consumption. This is especially important in multi-hop WSNs. A unique feature of the sensor networks is the cooperative work of sensor nodes, where multiple and multi-modal observations data is distributed to a central gateway (or another node) which is in charge for their processing. Instead of continuously sending raw data to the nodes responsible for their interpretation and processing, sensor nodes use their own processing capabilities to locally carry out simple computations and transmit only the required and partially processed data.

In a more specific sense and in context of defining the interoperability as a property of a 'thing', we consider the intelligence as the capability to perform any and every step of processing, needed for determining the meaningful and purposeful response to the perceived observations. This definition implies that the necessary condition for a cognitive activity is certainly an action. More important, it assumes purposefulness, which is socially determined. When processing requires computation which is not possible within a single node, this computation may be requested from its environment. Thus, as it was the case for the awareness attribute, intelligence cannot be considered in

isolation from the extroversion attribute. Also, it is tightly related to self-awareness, since a particular computation capability is an internal attribute of a 'thing'.

When discussing enabling technologies, a key thing to focus on is a particular kind of logic (or set thereof) that could facilitate inference in the context defined by the above attributes. Although most of the current efforts in developing sensor, IoT and WSN ontologies are implemented by using OWL, in authors' opinion this poses a serious constraint to the future developments related to enabling 'things' with intelligence. Namely, interoperability as a future property must also consider the possibility to *understand* and combine different formalisms and to make meaningful and unambiguous conclusions by using a variety of engines.

3.2. IaaP Impact on Disaster Management Organisations

To fully assess the impact of the IoT and IaaP paradigms impact upon the disaster management effort one must adopt an integrated approach, i.e. taking into account the interoperability extent, approach and aspects identified in Section 2 in the context of the enabling IaaP attributes described in Section 3.1.

In regards to the interoperability extent, the IoT and IaaP concepts would assist DMOs in gaining *agility*, thus being able to interoperate to a larger degree without having to become integrated within a specific negotiated framework or system of systems. Preserving organisation independence and resilience would prove crucial in emergency situations where disaster response task force partners may fail, with the rest of the team having to promptly reorganise and / or find replacements in order to recover missing functionality. This would require prompt, ad-hoc interoperation in areas not previously negotiated, which can be facilitated by acquiring IaaP. Thus, the DMOs will adopt a *federated* interoperability approach, now feasible in the context of IoT and IaaP.

As described in Sections 1 and 2, DMOs are highly heterogeneous and hierarchical, posing a variety of internal and external interoperability barriers. Thus, true and efficient collaboration is not possible unless the organisational cultures, processes and resources of the participants possess the required interoperability preparedness. Universal environmental awareness would greatly enhance the DMO's preparedness for cooperation, both inside and outside its own boundaries. Thus, on internal level, collaboration between various departments would be dramatically improved if all staff understood the way the organisation they belong to works at all levels; this understanding (namely, perception accuracy) should be supported by formal enterprise-wide repositories representing data and processes. The typically low interoperability degree of the current human, machine and hybrid systems would be replaced by ubiquitous awareness. On the external level, by displaying universal awareness the DMO would be able to seamlessly exchange information with other DMOs and relevant organisations and monitor heterogeneous disaster response crews' progress in real time, irrespective of location and taking into account ambient factors.

All DMOs feature some kind of knowledge management and/or business intelligence capability; however, typically they only cover the upper and possibly middle management levels. In the IaaP scenario, the knowledge management mechanism would evolve into an enterprise-wide ontology framework, extending from top management to the real-time response units, covering all relevant aspects, and enabled by a pervasive ubiquitous computing framework integrating intelligent sensors and controllers. In effect the DMO would now become a *learning organisation* that constantly adjusts and improves its response to external challenges in an agile manner.

The social effect of an extrovert DMO, materialised by transparency towards other DMOs, relevant organisations (e.g. community, non-governmental and faith groups, etc.) and general public would bring significant benefits. In large scale catastrophic events, trust and communication are paramount in an effective response and minimising negative effects. Often, in disaster situations, the population self-organises in novel and efficient ways; DMOs must tap into this resource and use it to optimize their operations. For this to happen however, in addition to gaining community trust (which cannot be rushed), DMOs must also be able to interoperate with the community at short notice and without previous preparation and negotiation – in effect displaying IaaP.

4. Interoperability of Everything (IoE) ontology

It has been considered useful to formalise the discussion above by synthesizing the identified concepts into an IoE (Interoperability-of-Everything) ontology. At this point, IoE ontology is only considered as an illustration of the principles for interoperability of ubiquitous systems. IoE appears to unfold around two central patterns: a horizontal pattern enclosing thing-attribute generic relationships and a vertical one defining the stimulus-observation-perception-decision-action cycle.

IoE extends the SSN ontology to stimulus-observation-perception-decision-action cycle (see Fig.4) in which the value of a stimulus is gradually added with the objective to perform both purposefully and socially. These aspects of the action are realized by the possibility of other 'things' to endorse the performed action, thus making one instance of the cycle a pattern of behaviour that can be later reused in identical or similar situations. Moreover, we distinguish between intrinsic and extrinsic intelligence. Intrinsic intelligence is exhibited if this cycle barely exists; e.g. the thing is intrinsically intelligent if it is capable to simply decide on the action. Extrinsic intelligence is exhibited if these actions have received the endorsement of other things.

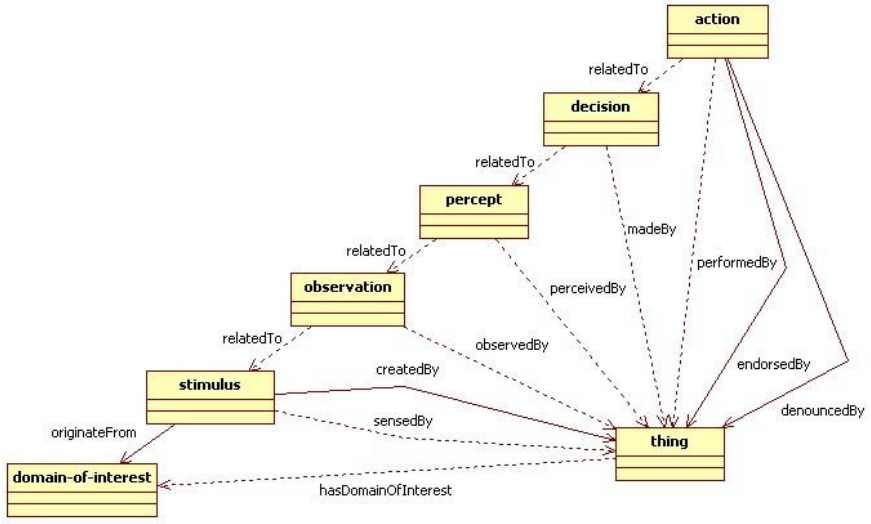

Fig. 4. UML representation of the central vertical pattern of IoE ontology

These concepts are related to the theory of systems intelligence proposed by Hämäläinen and Saarinen [52]. The systems intelligence is measured by successful interactions with an environment and a system's ability to modify its behaviour based on feedback from that environment.

In Fig. 4, dashed lines illustrate dependency. They indicate necessary conditions for concepts. Hence, a stimulus exists only if it is sensed – by a thing. However, it may be created by a thing. A thing has a minimum one domain of interest; however, it may sense a stimuli for which we do not know if it comes from any domains of interest, since originateFrom(stimulus, domain-of-interest) is not a necessary condition for a stimulus.
Fig. 5 illustrates the central horizontal pattern of IoE ontology, namely thing-attribute. All possible attributes are represented as individuals.

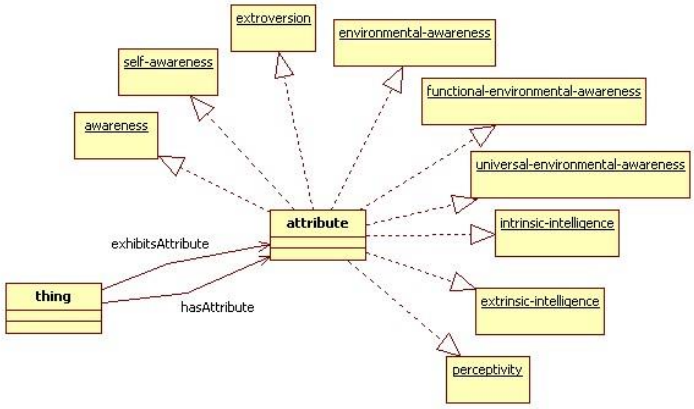

Fig. 5. UML representation of the central horizontal pattern of IoE ontology

In order to enable the evaluation of the interoperability property (namely, the related attributes) the assertion of things that do not exhibit above attributes by default is allowed. In other words, the association of a thing to an attribute is not a necessary condition for a thing.

Attribution to the things is asserted by the following rules:

[R1] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ exhibitsAttribute(t,'awareness')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(relatedTo(o,s) ∧ observedBy(o,t)))

[R2] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ exhibitsAttribute(t,'self-awareness')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(relatedTo(o,s) ∧ createdBy(s,t) ∧ observedBy(o,t)))

[R3] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ exhibitsAttribute(t,'environmental-awareness')) ⇒ ∀t(∃s(sensedBy(s,t) ∧ (not)createdBy(s,t)) ∧ ∃o(relatedTo(o,s) ∧ observedBy(o,t)))

[R4] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p)) ∧ exhibitsAttribute(t,'perceptivity')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(observedBy(o,t) ∧ relatedTo(o,s)) ∧ ∃p(perceivedBy(p,t) ∧ relatedTo(p,o)))

[R5] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ exhibitsAttribute(t,'intrinsic-intelligence')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(observedBy(o,t) ∧ relatedTo(o,s))

```
     ∧ ∃p(perceivedBy(p,t) ∧ relatedTo(p,o)) ∧ ∃d(madeBy(d,t) ∧
     relatedTo(d,p)) ∧ ∃a(performedBy(a,t) ∧ relatedTo(a,d)))

[R6] (thing(t) ∧ thing(t') ∧ stimulus(s) ∧ observation(o) ∧
     percept(p) ∧ decision(d) ∧ action(a)) ∧
     exhibitsAttribute(t,'extrinsic-intelligence')) ⇒
     ∀t(∃s(sensedBy(s,t)) ∧ ∃o(observedBy(o,t) ∧ relatedTo(o,s))
     ∧ ∃p(perceivedBy(p,t) ∧ relatedTo(p,o)) ∧ ∃d(madeBy(d,t) ∧
     relatedTo(d,p)) ∧ ∃a(performedBy(a,t) ∧ relatedTo(a,d)) ∧
     ∃t'(t≠t' ∧ endorsedBy(a,t')))
```

Note that relatedTo is a transitive symmetric property; hence it is possible to infer relatedTo(p,s) and relatedTo(a,s) in [R4] and [R5][R6], respectively. However, direct assertions of relatedTo(a,s) are also possible in cases when the 'thing' needs to make additional observations (and subsequent perceptions) in order to get some missing information from its environment (or from within itself), needed to complete the inference of the decision and, consequently formulated action.

Again, we highlight that the extrinsic intelligence is an attribute which is exhibited by a thing t, only if an action is performed by this thing, based on the set of stimuli it sensed, and only if there exist at least another thing t', which endorsed this action.

4.1. Modelling Intelligence

The above rules can be used only to validate if there exist stimulus-observation-perception-decision-action cycles where a thing exhibits one or more of the attributes. They are only formal definitions of these attributes. However, substantial intelligence of the 'thing' as its attribute can be confirmed if (and only if) intelligence is exhibited for *all* these cycles.

The assumption that the 'things' act upon every observation they make may sound too optimistic. However, we should take into account that the mere storage of the sensation-observation-perception triple can be considered as an action. These asserted triples can later be used for experience-based reasoning.

We discuss about substantial intelligence in context of the observation sets. An observation set is a set of observations, all of which are related to an action. This context is anthropomorphic because it involves consciousness: it does not consider all stimuli sensed by the 'thing' but only those that are observed (and in fact, acted upon). Thus, the member-of-observation-set class is defined as equivalent class:

```
member-of-observation-set ≡ observation(o) ∧ (action(a) ∧
relatedTo(o,a))
```

All observations are automatically classified to this class if the above conditions are met. All observations that are related to a single specific action are considered as the members of one observation set.

Also, we discuss about substantial intelligence in context of the perceptual sets. Similarly to an observation set, a perceptual set is a set of percepts, all of which are related to an action.

member-of-perceptual-set ≡ percept(p) ∧ (action(a) ∧ relatedTo(p,a))

The definitions of the above two equivalent classes are introduced to illustrate that we distinguish meaningful observations and percepts from the non-functional ones. In fact, during the process of deciding on the possible action, the 'thing' may look up among the relationships between the existing members of these two classes (and resulting actions), similarly to human mind's consideration of knowledge and experience.

While the 'occurrences' of intelligent behavior are formalized by exhibitsAttribute relationship, the substantial intrinsic [R7] and extrinsic intelligence [R8] of the 'thing' are represented by the inferred hasAttribute(thing(t), 'intrinsic-intelligence') and hasAttribute(thing(t), 'extrinsic-intelligence') relationships. These relationships are inferred, based on the following rules:

[R7] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ hasAttribute(t,'intrinsic-intelligence')) ⇒ ∀t(∀s(sensedBy(s,t)) (∀o(observedBy(o,t) ∧ relatedTo(o,s)) (∀p(perceivedBy(p,t) ∧ relatedTo(p,o)) (∀d(madeBy(d,t) ∧ relatedTo(d,p))))) ∃a(performedBy(a,t) ∧ relatedTo(a,d)))

[R8] (thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ hasAttribute(t,'extrinsic-intelligence')) ⇒ ∀t(∀s(sensedBy(s,t)) (∀o(observedBy(o,t) ∧ relatedTo(o,s)) (∀p(perceivedBy(p,t) ∧ relatedTo(p,o)) (∀d(madeBy(d,t) ∧ relatedTo(d,p))))) ∃a(performedBy(a,t) ∧ relatedTo(a,d)) ∧ ∃t'(t≠t' ∧ endorsedBy(a,t')))

Note that according to the proposed definition, the substantial extrinsic intelligence is inferred in case of endorsement of only one thing t', different from t. In simple words, if performed action is useful for at least one another thing, the behaviour is characterized by intelligent, independently of the possible denouncements or indifference of the other things in the environment.

4.2. IoE Ontology application to Disaster Management

In disaster management, the significant flow of information (especially in the initial so-called 'chaos phase' when the growth of this flow is explosive) may introduce confusion

about the meaning and correct context required to understand the information received from specific sensors. Thus, perceptivity is a critical capability of the devices in the cyber physical eco-system that are relied upon to assist in disaster management. In fact, active, or iterative perception will be often employed in order to to discover the context of understanding and thus, to facilitate a correct perception of the received information. The efficiency and effectiveness of such process largely depend on the *expressivity* of the perceptual sets that a device will use to discover the context. An important role in these perceptual sets is played by the disaster management ontologies;

IoE ontology facilitates discovery of sensors by other devices based on the provided geographic area, desired time interval and desired properties to be observed. It also enables the formal definition of the domain of interest for one device, which is constituted based on some of the Dolce's 'SpatioTemporalRegion' and 'Feature of Interest' instances of the SSN ontology [41]. In fact, the semantic definition of the latter is the most difficult challenge a one device that needs to discover some relevant information, because it assumes the understanding of the domain specific concepts (e.g. environmental, chemical, etc.). An obvious way to resolve this challenge is to map IoE ontology (in fact, the above SSN-defined input concepts) to domain-specific descriptions of features of interest and geographical objects, respectively. A strong candidate with needed formal descriptions is Geosensor Discovery Ontology (GDO) [58]. It defines: 1) the terminology of phenomena, namely properties than can be observed by sensors; 2) taxonomy of substances to which phenomena above may pertain; 3) taxonomy of geographic objects to which above phenomena may pertain; 4) logical relationships between all above. GDO is intended to be used for semantic annotations of SOS (Sensor Observation Services) defined services [59].

IoE's domains of interest combine the SSN's features of interest, semantically defined by GDO, with spatio-temporal regions also to clearly express the mutual effects of the different phenomena and regions. Subsequently, these effects can be used for active perception in events that cannot be explained with the current set of observations, (which set however, is a subset of the previous observations that lead to the specific event inferences).

For example, the observation of extreme air pollution over a chemical plant alone does not necessarily imply a possible environmental incident. However, when combined with a specific weather phenomenon, it might. Let's assume that there is a water purification plant, located at the distance from the chemical plant, and it uses water from the river that also passes by the chemical plant. A heavy rain may cause critical river pollution, affecting the water purification facility. In IoE, such a set of related observations are declared members of a single observation set (not a named entity) that trigger some specific decision and may further on trigger some action. Figure 6 illustrates a partial view of the observations (O), perception (P) and action (A) instances of IoE ontology in above example.

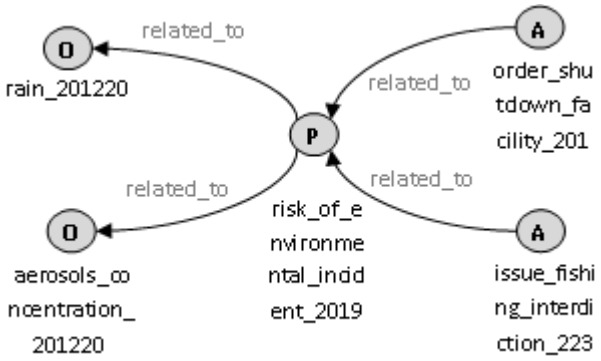

Fig. 6. Partial view of the example instances of the IoE ontology vertical pattern

Since all the ontologies that are used to formally describe the observation set are being parts of the ontological frameworks used by all devices, the assumption is that all devices can trigger a specific decision, e.g. to infer the environmental incident instance.

To follow-up on the above case of the environmental incident caused by the observed air pollution and heavy rain, there are two possible actions to be carried out by the various devices. Firstly, the water purification system may automatically issue a shutdown command or specific dispensers may be activated to use change purification substances to compensate for the presence of specific chemical compounds in river. Second, a ranger's smart-phone may issue a notification prohibiting river fishing.

5. Conclusions and Further Work

In this paper, we argue that the interoperability as a property of ubiquitous systems can be achieved if these systems are empowered with the attributes of awareness, perceptivity, intelligence and extroversion. Such an empowerment would make an important contribution not only to the theory and practice of disaster management, but also in all areas where the effectiveness of the systems depend on the cooperation and agile response by both, humans and devices. The above attributes enable the systems to behave and communicate autonomously and openly, independently of the designated features of interest, similarly to humans, in the activities of sensation, perception, cognition and articulation.

Social agreement is needed to provide validation of a pattern of system behaviour, possibly transforming it into templates of behaviour, namely vertical IoE patterns. The reliability of such validation is argued by the fact that it occurs in a multi-faceted framework, where a specific system action is judged in the different contexts where the various other systems live.

One of the most obvious and direct effects of such an approach in the future are related to addressing key technological challenge of WSNs: decrease the energy consumption of ‘things’ and extend the lifetime of the nodes. Furthermore, encoding some kind of intelligence into individual things contributes significantly to the possibility of networks of ‘things’ to scale more effectively and efficiently, even across the boundaries of other networks. This future benefit is derived from the foreseen capability of ‘things’ to sense, perceive and act independently of the predetermined features of interest.

The amount of research opportunities in this area is immense, even without considering the technical (hardware) challenges. They are mostly related to the development of top-level theories and strategies which are not foreseen to replace or update current approaches, but rather to reconcile them, by enabling ‘things’ proficiency in different standards, languages and even logics.

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