

1 Introduction

According to IDC (www.idc.com) – a global provider of market intelligence, advisory services, and events for the information technology, telecommunications and consumer technology markets – the worldwide shipment of smart connected devices will surpass 2.5 billion units in 2017. As the cost, size, and power requirements keep decreasing, computing will be embedded in all kinds of products and everything that can benefit from the Internet will be connected. Not only stations, computers or laptops, but also tablets, smartphones, cars, game consoles, TV sets, cameras, machines, lights, locks, and home appliances.

People and data are already online. Soon, all sort of things with sensors, actuators and places will be also online. All sectors of activity will benefit from applications that leverage the interconnection of embedded systems with IT systems. Intelligent transport solutions can speed up traffic flows, reduce fuel consumption, and save lives. Smart farming solutions will improve the production and delivery of safe and healthy food. Remote health monitoring will provide convenient access to healthcare, raises it quality, and save money. Utilities management, education, government services, retail sectors etc. all will also benefit from such couplings and the things will leave across all different systems. **The next step is to interconnect these individual systems into a system of systems, and here we are confronted to such a scale and heterogeneity that we are reaching a limit in networking and software engineering.**

In this project, we aim to investigate issues related to the design and development of a secure physical and computational networked environment, consisting of billions of connected smart objects (things), which allows interoperability and facilitates efficient collection and processing of data and analytics. These smart objects may come from diverse environments such as smart appliances at homes, smart mobile surveillance system such as fire trucks and police cars, smart transportation entities (e.g., cabs or buses), etc. By establishing a dynamic instantiations of Internet of Things (IoT) structures, we aim to provide an automatic resource optimization and other intelligence into these evolving collections of smart connected objects. However, rather than endowing them with autonomously cognitive chips, we ask for manufacturers, retailers and users/owners, through an established social network of things, to elaborate finely tuned dispatches to be distributed toward the smart objects through middleware fogs located in the individual homes.

Nowadays, existing start of the art related to the design of IoT systems is highly compartmentalized, the data collection and analytics processing across a variety of heterogeneous IoTs has limited support, and the interoperability of objects across domains has not been addressed at a level that would provide the kinds of optimizations that this project aims.. In this project, we introduce the concept of collaborative Social Network of Things that would enable data and analytics sharing across objects that exhibit similar operating characteristics and/or have similar profiles in terms of usage and user/manufacture parameters. In addition, we propose to develop a hierarchical middleware implemented as fogs to allow interoperability with context-aware security properties associated with different nodes. These middleware fogs, mainly implemented in smart boxes/gateways within local networks, will manage the communication between the associated smart objects and the network in an optimized way that takes into account both the characteristics of the smart objects and the preferences of the users. The massive generated data by all these connected smart objects and stored in the system will enable the cognitive network, through deep learning algorithms, to raise dynamic procedures that will enable a multi-criteria optimizations of the behavior of these smart objects.

A typical scenario could be as follows. During his coffee break at the office, Jack decides to lower by 5 degrees the set point temperature of his home heating system which must go into action when he is less than 1 mile from his home and in any case no later than 6PM. However, if the outside temperature drops below certain threshold, the temperature must go up by 5 degrees. At lunchtime, a colleague of his gives Jack a list of instructions corresponding to a new method for washing wool sweaters; he sends the file directly to his home through the social network where a service will adapt the instructions to that washing machines particular technical features and his personal preferences for extra soft cloths. Back at home, Jack launches my angry day profile through smartphone, which automatically dims the light and has the Hi-Fi play his favorite relaxing music. Meanwhile, a tip from the network tells Jack to turn off all TVs to avoid getting further depressed. During the night the washing machine starts the cycle at the time the electric company informs it to be the most favorable.

While the above describes a single user, what we aim to investigate in this project is how to incorporate multiple users and smart devices into multiple instances of Social Network of Things, that can be generated/organized and dissolved on-the-fly; where different criteria can be used to orchestrate the behavior of (groups of) instances subject to multiple constraints; and certain security and privacy concerns are ensured. In the context of Jack scenario, this would mean collaboratively regulating the temperature with other units in Jacks building; collaboratively deciding about the cycle

of the washing machine in terms of optimizing the grid-demand within a city-block; adjusting the Hi-Fi themes based on the fact that Jack decided to join his co-workers for a happy-hour; etc. Moreover, we plan to provide novel data analytics methodologies that will: (a) incorporate the fact that some users may not be cooperative in terms of suggested regime of use for certain devices/task; (b) provide a specific behavioral insights to be used by various manufacturers when planning the design of certain devices so that they can be better adapted to changing conditions of use. The architecture we target to support such scenarios is depicted in Figure 1. We aim at providing methodologies and tools for two basic modes:

(1) The first setup consists of a set of middleware fogs, located in each smart box/gateway of a smart home or public area, grouped together in a social network along with profiles of manufacturers, retailers and users/owners. The lower layer is formed by all the real devices/objects (things), such as a fridge, a washing machine, a heater, a TV, a Hi-Fi, etc., where each one is abstracted by what we refer to as WiThing (WiT) for Wireless Thing. The WiT is the first level of the device abstraction and its role is to (1) uniquely identify an object/device worldwide, (2) represent the object in terms of its properties/functionalities through an MIB (Management Information Base), and (3) constitute a bidirectional interface for all communications between the object and the middleware fog located in the smart box/gateway. The intermediate layer contains the smart box/gateway where the middleware fog is implemented. The latter is composed of an ensemble of interconnected modules that will govern all the requests issued by the user through a proper front-end application. To this end, this smart box must interface with any object/device it meets in the surroundings, i.e., any virtual device communicated by the real objects/devices. The upper layer contains the social networks of manufacturers, retailers and users/owners with the generic representations (avatars) of their objects/devices. It consists of a large database with an enquiry system based on sophisticated algorithms. Throughout this complex environment, and in order to fully automate the deployment and control of such Internet of Things, gathering of important data, identification of correlations in this chain of complex events, and triggering the required responses, a plethora of issues in data collection and processing (storage/retrieval, querying and information fusion), knowledge discovery, and security and privacy need to be investigated in unified framework. We assert that such integrated large scale effort, involving researchers from diverse backgrounds, is necessary to enable exploiting the full potential of the Internet of Things technology and make it ubiquitous of use.

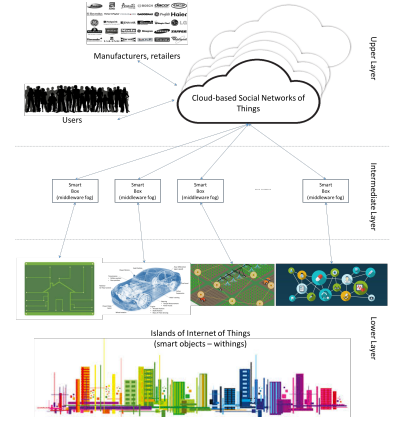


Fig. 1: An overview of the system

(2) The second setup complements the previous one in terms of inter-contexts couplings and dynamic formations (and dissolution) of corresponding Avatars. In terms of notation in Figure 1. it is best explained by the following scenarios: (a) If we have a collection of Avatars corresponding to a particular device (e.g., a washer) in a collection of residential units, depending on the geographical context we may want to form different instances of (meta)Avatars corresponding a group of same devices but operating in: (i) a group of houses in a suburban residential area; and/or (ii) a group of buildings in a near-downtown area. (b) Complementary to this, the Avatars corresponding to washers in different units in an apartment complex, may be tied with the Avatars corresponding to entertainment devices in the same and/or neighboring buildings. (c) The collection of Avatars representing the traffic-density in different geographical regions may be tied with the crime-rate in those and/or near-by regions and with the ones corresponding to activities of electronic devices in the police cars. However, after a certain time of the day/night, such (meta)Avatars may cease to exist.

The situational awareness that we aim to capture by dynamically creating Meta-Avatars is illustrated in Figure 2. We note that, in addition to the scenario-oriented discussion above, the Meta-Avatars may be created based on:

- Particular cyber-properties: e.g., status of network infrastructure, privacy constraints, etc. Logical or semantical properties which may entail dynamically forming (and dissolving) hierarchies of such avatars.

The main Intellectual Merits of the proposed project are: —Repeat the Intellectual Merits here

2 State of the art

We now present an overview of the state of the art, both from the perspective of the current properties of devices and networking technology features, as well

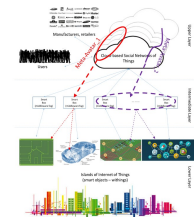


Fig. 2: Meta-avatars

as from the perspective of related works in several fields that, in one way or another, may be used to achieve our objectives however, they fall short of several important aspects.

2.1 Whatever Proper title of this sub-section

The vast majority of devices are endowed with electronic interfaces, made of buttons and the like, inviting users to operate selections from among a limited set of options pre-featured by the manufacturers. They may concern options, such as, ventilation on/off button in an oven, a selection of delicate option in a washing machine, air-condition on/off button in a car, and so on. While these older devices are considered somehow efficient and simple, the trend is towards more technological and ubiquitous devices. The operational innovation of our approach is to make a move of the interface a step ahead and a step farther so as to realize a deep, remote and smart control. In this case, the manufacturer makes all/most of the operational parameters, such as spin speed and duration, totally manageable and configurable by the user. In turn, the user drives these parameters via software, hence makes them obeying to automatic procedures/instructions that have been elaborated and optimized in advance, with the help of the manufacturer, other contributors, and/or the networked intelligence. Thus, we need to have this new hardware/software interface managing signals/data back and forth between actuators/sensors and a logic unit with the result of detaching the user from any physical contact with the device (thing). To this end, in the project we will use open source electronic boards, such as Arduino boards (<https://www.arduino.cc/>), Parallella boards (<https://www.parallella.org/>) and/or Raspberry-Pi boards (<https://www.raspberrypi.org/>). They are powerful prototyping boards based on flexible, open and easy-to-use hardware and software. These devices are wirely and/or wirelessly connected to the Internet from which they can be easily visible and accessible. We foresee that their exploitation will lead microelectronic companies to develop specific chips for a massive diffusion of this new technology in a near future. In order to realize the vision of an Ambient Intelligence in a future network and service environment, heterogeneous wireless sensor and actuator networks have to be integrated into a common framework of global scale and made available to services and applications via universal service interfaces [25]. The goal is to reach a distributed open architecture with interoperability of heterogeneous systems, neutral and easy access, clear layering and resilience. It should provide the necessary network and information management services to enable reliable, secure and accurate interactions with the physical environment. The idea is to provide an integrated platform that offers unified data access, processing and services on top of existing ubiquitous services of the Internet of Things to integrate heterogeneous sensors/actuators in a uniform way. From an application perspective, a set of basic services encapsulates sensor/actuator network infrastructures hiding the underlying layers with the network communication details and heterogeneous sensor hardware and lower level protocols.

A heterogeneous networking environment indeed calls for means to hide the complexity from the end-user, as well as applications, by providing intelligent and adaptable connectivity services, thus providing an efficient application development framework. To face the coexistence of many heterogeneous set of things, a common trend in Internet of Things applications is the adoption of an abstraction layer capable of harmonizing the access to different devices with a common language and procedures [11]. Standard interfaces and data models ensure a high degree of interoperability among multiple systems. However, typical drawbacks of misconfigurations and traffic congestions are normally exasperated by the node heterogeneity. These drawbacks will be overcome in the project through the adoption of islands architecture. On the one hand, smart gateways in their locations will hide all the complexities of the underlying standards. Hence, wireless connections of the devices/machines to the web/Internet, using communication technologies like Zigbee [3], Z-wave [38], Wi-Fi [39], plus the mapping of every device to a unique ID, will provide full, intelligent and secure control over it. With these smart boxes/gateways, technological limitations will completely disappear and the devices will become identifiable only through their functionalities with clear and consistent APIs. On the other hand, the middleware fog constitutes an abstraction level where all the devices, viewed as entities sharing their functionalities (avatars), are transparently managed and used. The goal is to manage the collaboration between heterogeneous devices through a simple API level in conjunction with the mentioned communication protocol able to reach the peer within the location singularly.

Most existing solutions for middleware adopt in general a service-oriented design tailored mainly to support a network topology of sensors that is both unknown and dynamic. But while some projects focus on abstracting the sensors in the network as services (such as in HYDRA [12, 40, 41], SENSEI [32], SOCRADES [13], and COBIS [33]), other projects devote more attention to data/information abstractions and their integrations with services (among which are SOFIA [16], SATware [26], and Global Sensor Networks GSN [1]). A common thread throughout all of these solutions, however, is that they handle the challenge of an unknown topology through the use of discovery methods that are largely based on the well-known traditional service/resource discovery approaches of the existing Internet, ubiquitous environments and wireless sensor and actuator networks [2, 27, 42]. For instance, SOCRADES provides discovery

on two levels, the sensor level and the service level, which can employ either standard web-service discovery or a RESTful discovery mechanism (for RESTful services). COBIS, on the other hand, uses its own service description language COBIL 2 (Collaborative Business Item Language), where service functions and keywords are annotated with a verbal description. Another point of agreement in the state-of-the-art of middleware solutions is in the widespread use of semantics and metadata to overcome heterogeneity challenges. Indeed, it is standard practice to use ontologies to model sensors, their domains, and sensor data repositories [10, 12, 24]. Some projects even go a step further and also include context information [32], or service descriptions [12, 40, 41]. And as a type of service composition, many projects support the concept of virtual/semantic sensors (for instance, in HYDRA, GSN and SATware), i.e. entities that abstract several aggregated physical devices under a single service. A different implementation of a similar idea, though, is provided in the SATware project, where virtual sensors actually correspond to transformations applied to a set of raw sensor streams to produce another semantically meaningful stream.

Regarding scalability, most projects address this challenge by pursuing modifications in the underlying sensor/actuator network topology. Sometimes, this is done by adopting fully-distributed infrastructures (such as in COBIS and SOFIA), and sometimes through an architecture of peer-to-peer clusters (e.g., GSN). In our view, however, while these approaches work well for the existing Internet, where traffic is made up of a relatively small amount of service interactions, they will not fit for the complex weave of interactions that will be commonplace in the Internet of Things. In the Internet of Things, a large number of requests will involve intricate coordination among millions of things and services, whereas on today's Internet most requests are largely point-to-point. Therefore, the number of packets transmitted in the network will grow strongly and nonlinearly as the number of available services increases. In such an environment, performing even a simple service discovery may exceed acceptable time, processing, and memory constraints. //NOTE: the last paragraph needs to be tied (cf. (2)/Fig.2 in the intro with the problems related to "Possible Worlds Semantics" and the efficient pruning the needs to be performed

2.2 Data and Process Integration

Heterogeneous data integration is a topic which, in addition to the database community broadly [8, 14], has also been investigated by more specialized research foci: – bioinformatics [22, 28]; information management and text retrieval [9, 15, 37]; sensing/actuation and tracking [4, 7, 34] (to name but a few). While the role and the impact of the semantics have been recognized and addressed [5, 6], the existing results still have limited cross-contextual support. For instance, the works investigating the benefits of semantics for resource discovery (cf. [6]) do not take into consideration the role of different devices that may enter and/or leave a particular "geo-social" network dynamically, as well as their impact on real-time adjustments (as well as the impact of their cessation). To-Do – Goce: Overview of:

- a. Data integration + distributed query processing; workflows [23, 29, 30]; Wireless Actuator Networks
- b. Analytics and platforms in-context (Cloud/Hadoop; NoSQL; Warehousing) [36]

3 Proposed research overview

We now proceed with identifying the main challenges that the proposed project will address, with a brief overview of the proposed research tasks (research challenges), followed by an introduction of the team and their expertise.

Research Challenge 1 (RC-1): Data collection and processing

Research Challenge 2 (RC-2): Knowledge discovery

Research Challenge 3 (RC-3): Security, privacy (anonymity) and trust

The Internet of Things is foreseen to bring a multitude of services with a vision of creating a smart self-configuring and interconnected world for the benefit of end users. With the extensive research and development of computer, communication and control technologies, it is possible to connect all things to the Internet such that the so-called Internet of Things (IoT) can be formed. These things may be equipped with devices such as sensors, actuators, and tags, in order to allow people and things to be connected anytime and anywhere, with anything and anyone. IoT will enable collaborations and communications among people and things, and among things themselves, which expand the current Internet and will radically change our personal, corporate, and community environments. However, a plethora of secu-

rity, privacy, and trust challenges need to be addressed in order to fully realize this vision [20, 21, 22, 23]. When more and more things connect to the Internet, security and privacy issues become more serious, especially in the case that these things are equipped with actuators and can support control. For better protection of secure communication and user privacy, including location, identity and behavior habits, it is necessary to develop anonymous communication theories, methods and key technologies of anonymous communication systems in all varieties of application environments. Anonymous communication is used to hide communication participants or communication relations to achieve effective protection for network nodes and user identities. Anonymous communication can address potential network security issues, and becomes one of the hot topics in the field of network and information security. With reference to security, data anonymity, confidentiality, and integrity need to be guaranteed, along with providing authentication and authorization mechanisms in order to prevent unauthorized users (i.e., humans and devices) to access any system. Concerning privacy requirement, both data and user personal information have to be confidentially manipulated since devices may manage sensitive information (e.g., user habits, locations, etc). Finally, trust is also a fundamental issue since the IoT environment is characterized by multiple devices that have to process and handle the data in compliance with user needs and rights.

To realize a trusted, secure, and privacy preserving social network of things, we plan to address in this proposal the following security, privacy, and trust management related tasks:

T-3.1: Define a new scheme of anonymizing things and representing them as avatars in the social network of things.

T-3.2: Authentication of data collected in fogs in the presence of malicious attackers, despite the attack surface being very broad, ranging from PHY layer to application layer.

T-3.3: Achieving end-to-end secure and privacy-preserving information flow monitoring between users and things, covering all sort of things and access networks using physiological and physical layer properties.

T-4.3: Design of secure, fast and friendly authentication schemes to allow users of the social network of things to access the data of interest through diverse mobile devices such as smartphones and tablets.

4 Research tasks

We now proceed with a detailed presentation of the main research of the proposed project.

4.1 Data collection and processing

(Goce + Mubbasir)

Data cleaning, data collection, sharing, processing, analytics

How can we secure the collected data and how to make it available?

APIs and libraries for building applications

ADAPT [35] BSTL [18, 21] behavior authoring [17, 20] story world [31] CANVAS [19]

smart object representation – attributes and relationships

4.2 Knowledge discovery: social network of avatars (virtual world)

(Ashfaq + Vladamir)

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4.3 Security, privacy and anonymity

(Farid + Alex)

Data security

System level security

Privacy, anonymity

Greedy behavior (?)

Key sharing problem

Privacy, trust and anonymity

4.4 Implementation and validation

(All)

Letters of Collaboration)

Campus wide implementation

Letters of Commitment

Shall we rely on KAA?

APIs: flexibility of formats/schemas

Given the interdisciplinary nature of the tasks in the proposed project, it is necessary to have well-defined mechanisms for assessing the validity and benefits of our findings. We will base our demonstration on variations of the two methodologically interdependent scenarios used in the introductory section. We now discuss both the broad categories of evaluation environments, and the details of the particular evaluation methodologies. We will adopt a three-fold analysis of the different aspects of our system: (1) agent-based computer simulations, (2) experiments with real humans controlling avatars in shared virtual worlds, and (3) experiments with real humans in actual real-life environments. Each of these experimental paradigms allow us stress our system along a combination of the following three axes: (1) human stress, (2) replicating the noise inherent in using humans as sensors, and (3) scalability ? i.e., the number of participants (humans or agents). Agent-based simulations harness computation to simulate high-stress events in arbitrarily large crowds of computer agents, but are unable to accurately model humans. Shared online virtual worlds provide a unique opportunity to conduct experiments with real humans in controlled settings. While experiments with human subjects in the real world offer the closest possible parallel to reality, these experiments are limited in number of subjects and the extent of stress that we can induce on the participants. However, by leveraging combinations of all 3 paradigms, we are uniquely positioned to evaluate our models and technologies in a rigorous manner.

4.4.1 Simulation-based Evaluations: Agents.

The first part of our efforts will focus on developing simulator for the two demonstration settings. Throughout the different phases of the project we will be capitalizing upon ? as well as augmenting the current capabilities of ? the SIDnet SWANS simulator [195] and SteerSuite: The Human Movement and Crowd Simulator [196], being developed at Northwestern and Rutgers respectively. SIDnet is used to evaluate various routing and tracking protocols, shapes detection, and even to evaluate the benefits of high-level programming constructs for WSN-users [113, 160, 187, 191]. SteerSuite is an open-source framework for simulating human movement, deliberation, and is especially geared towards dense crowd situations. We will integrate the functionality of these two systems and further augment them with the capability of having heterogeneous nodes and capturing various mobility models and communications between subsets of such nodes. In addition, we will augment its visualization component as well as introduce a new class of nodes with the proper interfaces to encode the following important features: (1) camera/video/audio based sensing and (2) human and human-operated sensors. For the multimodal mashup scenario, we will simulate a simplified version of the ?Gold Miner? using computer imagery, with virtual objects and sensors. The main use of the simulator in the initial stages of the proposal will be to test the various impacts of uncertainty (sensors, network structure/communication) on the quality of detecting the novel categories of spatio-temporal predicates (cf. Section 3.4) and the impact of different policies for local state-estimation and information extraction (cf. Section 3.1 and 3.3). We will employ a large variety of crowd datasets to train and validate our computational models, and in particular leverage our collaboration with Prof. Dirk Helbing who has significant expertise in crowd data collection, analysis, and modeling [197]. In particular, we will integrate our simulation infrastructure with the NervousNet platform [198] that is being actively developed by Prof. Helbing and his colleagues as part of the larger effort on the Planetary Nervous System project [199], which provides a large-scale distributed research platform for real-time mining of social activities using heterogeneous sensor networks.

4.4.2 Task E-2. Game Playing Evaluation: Avatars.

Agent-based simulations, such as those described above provide an efficient way to test and evaluate the different aspects of our system in an automated fashion. However, in an effort to come closer to actual human experimentation, we will conduct experiments using real human users in shared online virtual environments. The Rutgers team is uniquely

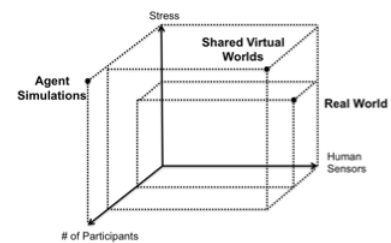


Fig. 3: Evaluation using Agent simulations, Shared Online Virtual Worlds, and Real World Experiments.

positioned to conduct these experiments ? Co-PI Kapadia has developed HeapCraft [200, 201]: a modular, extensible, and open framework for studying human behavior in shared virtual worlds such as Minecraft. HeapCraft has already been successfully demonstrated to study player behavior and incentivize cooperation in online societies [202, 203]. Additionally, Kapadia and his collaborators have also conducted lab experiments to study crowd evacuations using serious games. We will augment the existing HeapCraft framework to design the two scenarios described in Task E-3 below. HeapCraft's modular and extensible nature allows us to easily develop emulators for the technologies being developed here, which can be rigorously and robustly tested in shared virtual worlds using real human users. In addition, we will augment the knowledge-base for emulating behavioral aspects of the avatars using large datasets of preferences and semantic relations from real social networks obtained from 4C Insights Inc. (Letter of Commitment is available in the Supplementary Documents). Our experiments will be conducted in two phases: (I) laboratory studies where up to 40 participants will be recruited to participate in a controlled experiment; (II) online server with our tools released to setup a virtual world with hundreds of human-users expected to participate.

4.4.3 Task E-3. Real-World Environment Evaluations.

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5 Broader Impact

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6 Results from current and recent prior NSF support

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7 Data management plan

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8 Project management plan including timeline

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References

- [1] K. Aberer, M. Hauswirth, and A. Salehi. Infrastructure for data processing in large-scale interconnected sensor networks. In *International Conference on Mobile Data Management*, 2007.
- [2] E. Al-Masri and Q. H. Mahmoud. Investigating web services on the world wide web. In *17th international conference on World Wide Web. ACM*, 2008.
- [3] ZigBee Alliance, 2012.
- [4] Besim Avci, Goce Trajcevski, and Peter Scheuermann. Tracking uncertain shapes with probabilistic bounds in sensor networks. In *Advances in Databases and Information Systems - 20th East European Conference, ADBIS 2016, Prague, Czech Republic, August 28-31, 2016, Proceedings*, pages 338–351, 2016.
- [5] Sonia Bergamaschi, Silvana Castano, Maurizio Vincini, and Domenico Beneventano. Semantic integration of heterogeneous information sources. *Data Knowl. Eng.*, 36(3):215–249, 2001.
- [6] Silvana Castano, Alfio Ferrara, Stefano Montanelli, and Gianpaolo Racca. A semantic approach for resource discovery in distributed systems. In *Proceedings of the Twelfth Italian Symposium on Advanced Database Systems, SEBD 2004, S. Margherita di Pula, Cagliari, Italy, June 21-23, 2004*, pages 442–450, 2004.
- [7] Sudarshan S. Chawathe, Venkat Krishnamurthy, Sridhar Ramachandran, and Sanjay E. Sarma. Managing RFID data. In *(e)Proceedings of the Thirtieth International Conference on Very Large Data Bases, Toronto, Canada, August 31 - September 3 2004*, pages 1189–1195, 2004.
- [8] William W. Cohen. Integration of heterogeneous databases without common domains using queries based on textual similarity. In *SIGMOD 1998, Proceedings ACM SIGMOD International Conference on Management of Data, June 2-4, 1998, Seattle, Washington, USA.*, pages 201–212, 1998.
- [9] Adrien Coulet, Yael Garten, Michel Dumontier, Russ B. Altman, Mark A. Musen, and Nigam H. Shah. Integration and publication of heterogeneous text-mined relationships on the semantic web. *J. Biomedical Semantics*, 2(S-2):S10, 2011.
- [10] M. Eid, R. Liscano, and A. El Saddik. A universal ontology for sensor networks data. In *IEEE International Conference on Computational Intelligence for Measurement Systems and Applications*, 2007.
- [11] M. Eisenhauer, P. Rosengren, and P. Antolin. A development platform for integrating wireless devices and sensors into ambient intelligence systems. In *Sixth Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops*, 2009.
- [12] M. Eisenhauer, P. Rosengren, and P. Antolin. Hydra: A development platform for integrating wireless devices and sensors into ambient intelligence systems. In *The Internet of Things*, 2010.
- [13] D. Guinard, V. Trifa, S. Karnouskos, P. Spiess, and D. Savio. Interacting with the soa-based internet of things: Discovery, query, selection, and ondemand provisioning of web services. *IEEE transactions on Services Computing*, 3(3), 2010.
- [14] Alon Y. Halevy, Anand Rajaraman, and Joann J. Ordille. Data integration: The teenage years. In *Proceedings of the 32nd International Conference on Very Large Data Bases, Seoul, Korea, September 12-15, 2006*, pages 9–16, 2006.
- [15] Joachim Hammer, Hector Garcia-Molina, Kelly Ireland, Yannis Papakonstantinou, Jeffrey D. Ullman, and Jennifer Widom. Information translation, mediation, and mosaic-based browsing in the TSIMMIS system. In *Proceedings of the 1995 ACM SIGMOD International Conference on Management of Data, San Jose, California, May 22-25, 1995.*, page 483, 1995.
- [16] J. Honkola, H. Laine, R. Brown, and O. Tyrkko. Smart-m3 information sharing platform. In *IEEE Symposium on Computers and Communications (ISCC)*, 2010.
- [17] M. Kapadia, S. Singh, G. Reinman, and P. Faloutsos. A behavior-authoring framework for multiactor simulations. *Computer Graphics and Applications, IEEE*, 31(6):45–55, nov.-dec. 2011.

- [18] Mubbasir Kapadia, Jessica Falk, Fabio Zünd, Marcel Marti, Robert W. Sumner, and Markus Gross. Computer-assisted authoring of interactive narratives. In *Proceedings of the 19th Symposium on Interactive 3D Graphics and Games*, I3D '15, pages 85–92, New York, NY, USA, 2015. ACM.
- [19] Mubbasir Kapadia, Seth Frey, Alexander Shoulson, Robert W. Sumner, and Markus Gross. Canvas: Computer-assisted narrative animation synthesis. In *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, SCA '16, pages 199–209, Aire-la-Ville, Switzerland, Switzerland, 2016. Eurographics Association.
- [20] Mubbasir Kapadia, Shawn Singh, Glenn Reinman, and Petros Faloutsos. Behavior authoring for crowd simulations. In *Symposium on Interactive 3D Graphics and Games*, I3D '11, pages 199–199, New York, NY, USA, 2011. ACM.
- [21] Mubbasir Kapadia, Fabio Zund, Jessica Falk, Marcel Marti, Robert W. Sumner, and Markus Gross. Evaluating the authoring complexity of interactive narratives with interactive behaviour trees. In *Foundations of Digital Games*, FDG'15, 2015.
- [22] Toralf Kirsten and Erhard Rahm. Biofuice: Mapping-based data integration in bioinformatics. In *Data Integration in the Life Sciences, Third International Workshop, DILS 2006, Hinxton, UK, July 20-22, 2006, Proceedings*, pages 124–135, 2006.
- [23] Xiaorong Li, Rodrigo N. Calheiros, Sifei Lu, Long Wang, Henry Novianus Palit, Qin Zheng, and Rajkumar Buyya. Design and development of an adaptive workflow-enabled spatial-temporal analytics framework. In *18th IEEE International Conference on Parallel and Distributed Systems, ICPADS 2012, Singapore, December 17-19, 2012*, pages 862–867, 2012.
- [24] J. Liu and F. Zhao. Towards semantic services for sensor-rich information systems. In *2nd International Conference on Broadband Networks*, 2005.
- [25] A. Wolisz M. Sgroi and J. M. Rabaey A. Sangiovanni-Vincetelli. A service-based universal application interface for ad hoc wireless. In W. Weber, J. Rabaey, and E. H. Aarts, editors, *Ambient Intelligence*. Springer, 2005.
- [26] D. Massaguer, M. Diallo, S. Mehrotra, and N. Venkatasubramanian. Middleware for pervasive spaces: Balancing privacy and utility. In *10th International Middleware Conference Middleware: ACM/IFIP/USENIX*, 2009.
- [27] E. Meshkova, J. Riihijarvi, M. Petrova, and P. Mahonen. A survey on resource discovery mechanisms, peer-to-peer and service discovery frameworks. *Computer networks*, Elsevier, 52(11), 2008.
- [28] Sara Mostafavi and Quaid Morris. Fast integration of heterogeneous data sources for predicting gene function with limited annotation. *Bioinformatics*, 26(14):1759–1765, 2010.
- [29] Suraj Pandey and Rajkumar Buyya. Scheduling workflow applications based on multi-source parallel data retrieval in distributed computing networks. *Comput. J.*, 55(11):1288–1308, 2012.
- [30] Deepak Poola, Kotagiri Ramamohanarao, and Rajkumar Buyya. Enhancing reliability of workflow execution using task replication and spot instances. *TAAS*, 10(4):30, 2016.
- [31] Steven Poulakos, Mubbasir Kapadia, Andrea Schupfer, Fabio Zund, Robert Sumner, and Markus Gross. Towards an accessible interface for story world building, 2015.
- [32] M. Presser, P. Barnaghi, M. Eurich, and C. Villalonga. The sensei project: Integrating the physical world with the digital world of the network of the future. *IEEE Communications Magazine*, 47(4), 2009.
- [33] CoBIs project. Cobis final project report. Technical Report deliverable 104 v 2.0, [Online]. Available: <http://www.cobis-online.de/files/Deliverable D104V2.pdf>, 2007.
- [34] Hamidreza Salarian, Kwan-Wu Chin, and Fazel Naghdy. Coordination in wireless sensor-actuator networks: A survey. *J. Parallel Distrib. Comput.*, 72(7):856–867, 2012.
- [35] Alexander Shoulson, Max L. Gilbert, Mubbasir Kapadia, and Norman I. Badler. An event-centric planning approach for dynamic real-time narrative. In *Proceedings of Motion on Games*, MIG '13, pages 99:121–99:130, New York, NY, USA, 2013. ACM.

- [36] Adel Nadjaran Toosi, Rodrigo N. Calheiros, and Rajkumar Buyya. Interconnected cloud computing environments: Challenges, taxonomy, and survey. *ACM Comput. Surv.*, 47(1):7:1–7:47, 2014.
- [37] Riccardo Torlone. Two approaches to the integration of heterogeneous data warehouses. *Distributed and Parallel Databases*, 23(1):69–97, 2008.
- [38] Z wave Alliance, 2012.
- [39] Wi-Fi.
- [40] W. Zhang and K. Hansen. Semantic web based self-management for a pervasive service middleware. In *Second IEEE International Conference on Self-Adaptive and Self-Organizing Systems*, 2008.
- [41] W. Zhang and K. Hansen. An evaluation of the nsga-ii and mocell genetic algorithms for self-management planning in a pervasive service middleware. In *14th IEEE International Conference on Engineering of Complex Computer Systems*, 2009.
- [42] F. Zhu, M. Mutka, and L. Ni. Service discovery in pervasive computing environments. *Pervasive Computing, IEEE*, 4(4), 2005.