Self-aware cyber-physical systems and applications in smart buildings and cities

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Abstract— The world is facing several challenges that must be dealt within the coming years such as efficient energy management, need for economic growth, security and quality of life of its habitants. The increasing concentration of the world population into urban areas puts the cities in the center of the preoccupations and makes them important actors for the world's sustainable development strategy. ICT has a substantial potential to help cities to respond to the growing demands of more efficient, sustainable, and increased quality of life in the cities, thus to make them "smarter". Smartness is directly proportional with the "awareness". Cyber-physical systems can extract the awareness information from the physical world and process this information in the cyber-world. Thus, a holistic integrated approach, from the physical to the cyber-world is necessary for a successful and sustainable smart city outcome. This paper introduces important research challenges that we believe will be important in the coming years and provides guidelines and recommendations to achieve self-aware smart city objectives.

Keywords—Cyber-physical systems, Autonomic computing, Self-aware systems, Smart city

I. INTRODUCTION

Currently more than half of the world population lives in cities and the urban areas of the world are expected to absorb all the population growth expected over the next four decades while at the same time drawing in some of the rural population. Besides, on 2% of the earth's surface, cities actually use 75% of the world resources [1]. These facts make naturally the cities important actors for the world's sustainable development strategy.

One immediate action of the governments in the world has been to take measures in order to transform cities into "smart cities" that better manage their resources. ICT has a substantial potential to help cities to respond to the growing demands of more efficient, sustainable, and increased quality of life, thus to make them "smarter". Smartness is directly proportional to "awareness", which is defined in the literature as: the state or ability to perceive, to feel, or to be conscious of events, objects, or sensory patterns. With the spectacular advances in sensor and wireless technologies, we are now able to sense the physical events that occur in the environment, pre-process the events with embedded computing capabilities on the sensing devices and transmit them wirelessly to networked applications that can do perform more complex processing on data. Cyber-physical systems form the interface between the physical real world and the cyber world where information is processed, stored and exploited. CPS is very closely related to other emerging research topics such as Internet of Things, ubiquitous computing and pervasive systems. They are even commonly interchangeably used to mean similar concepts. Figure 1 illustrates this CPS vision.

Existing ICT solutions do not provide required support for applications to cope with dynamically changing physical context. Cyber-physical systems should thus bring the necessary mechanisms and tools that would make applications aware of the changes in the physical context [19], and adapt their execution according to it. By building such cyber-physical systems, an important step will be taken towards building the city nervous system that would provide the awareness to the city: the Smart City Ecosystem.

Autonomic computing [2], which has been proposed as a grand challenge for self-managing the increasing scale and complexity of ICT systems using high-level objectives and policies defined by humans, becomes even more important for cyber-physical systems that will exponentially increase the scale and complexity of existing computing and comunicaiton systems. The principle of Autonomic Computing consists of bringing to a given system the self-* properties such as self-adaptation, self-organization, self-optimization, self-configuration, self-protection, self-healing, self-discovery, self-description etc. There is still a lack of research on how to adapt and tailor existing research on autonomic computing to the specific characteristics of CPS, such as high dynamicity and distribution, real-time nature, resource constraints, and lossy environments. This paper introduces the related research issues and provides guidelines to achieve self-aware smart city objectives.

The rest of the paper is organized as follows. Section II presents essential properties of autonomic systems. Section III presents a general architecture of CPS. Section IV gives principal implementation guidelines for smart city infrastructures based on a cloud computing model. Section V concludes the paper and proposes some recommendations for future work in autonomic cyber-physical systems.

978-3-9815370-0-0/DATE13/©2013 EDAA

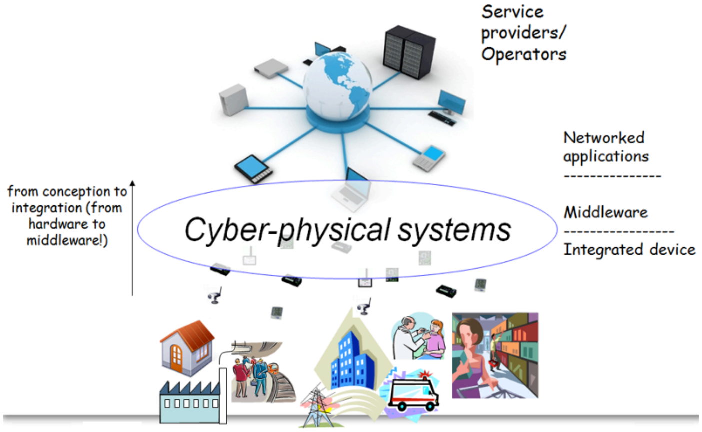

Figure 1. Convergence of the physical and the virtual world

II. PROPERTIES OF AUTONOMIC CYBER-PHYSICAL SYSTEMS

This section introduces various self-* properties that are particularly important for CPS systems.

A. Self-adaptation

In the very dynamic context of the CPS, adaptation is an essential property from physical to application layer. It allows the communicating nodes, as well as services using them, to timely react to the continuously changing context in accordance with high-level goals, for instance, business policies or performance objectives that are defined by humans. However, for the adaptation phase, human involvement must be minimized in order to deal with the intended large scale and reactiveness. The CPS should therefore be able to reason autonomously and give self-adapting decisions. Cognitive radios at physical and link layers, self-organizing network protocols, automatic service discovery and (re-)bindings at the application layer are important enablers for self-adapting CPS.

B. Self-organization

In CPS systems – and especially in WS&ANs - it is very common to have nodes that join and leave the network spontaneously. The network should therefore be able to re-organize itself against this evolving topology. Self-organizing routing protocols have a considerable importance in the CPS in order to provide seamless data exchange throughout these highly heterogeneous networks. Due to the large number of nodes, it is preferable to consider solutions without a central control point like for instance clustering approaches. When working on self-organization, it is also very crucial to consider the energy consumption of nodes and to come up with solutions that maximize the CPS system lifespan and the communication efficiency within that system.

C. Self-optimisation

Optimal usage of the constrained resources (such as memory, bandwidth, processor, and most importantly, power) of CPS devices is necessary for sustainable and long-living CPS deployments. Given some high-level optimization goals in terms of performance, energy consumption or quality of service, the system itself should perform necessary actions to attain its objectives.

D. Self-configuration

CPS systems are potentially made of thousands of nodes and devices (like sensors and actuators for instance) which therefore make the configuration of the system very complex and difficult to handle by hand. The CPS system should provide remote configuration facilities such that self-management applications automatically configure necessary parameters based on the (evolving) needs of the applications and users. It consists of configuring for instance device and network parameters, installing/uninstalling/upgrading software, or tuning performance parameters.

E. Self-protection

Due to its wireless and ubiquitous nature, CPS will be vulnerable to numerous malicious attacks. As CPS is closely related to the physical world, the attacks will for instance aim at controlling the physical environments or obtaining private data. The CPS should autonomously tune itself to different levels of security and privacy, while not affecting the quality of service and quality of experience.

F. Self-healing

The objective of this property is to detect and diagnose problems as they occur and to immediately attempt to fix them in an autonomous way. CPS systems should monitor continuously the state of its different nodes and detect whenever they behave differently than expected. It can then perform actions to fix the problems encountered (for instance by re-configuration parameters or installing a software update).

G. Self-description

Devices and resources (like sensors and actuators) should be able to describe their characteristics and capabilities in an expressive manner in order to allow other communicating objects to interact with them. Adequate device and service description formats and languages should be defined, possibly at the semantic level. The existing languages should be re-adapted in order to find a trade-off between the expressiveness, the genericity and the size of the descriptions. Self-description is a fundamental property for implementing plug-and-play resources and devices.

H. Self-discovery

Together with the self-description, the self-discovery feature plays an essential role for successful CPS deployments. CPS devices/services should be dynamically discovered and used by the others in a seamless and transparent way. Only powerful and expressive device and service discovery protocols (together with description protocols) would allow a CPS system to be fully dynamic (topology-wise).

I. Self-energy-supplying

And finally, self-energy-supplying is a tremendously important (and very CPS specific) feature to realize and deploy sustainable CPS solutions. Energy harvesting techniques (solar, thermal, vibration, etc.) should be preferred as a main power supply, rather than batteries that need to be replaced regularly, and that have a negative effect on the environment.

III. SELF-AWARE CYBER-PHYSICAL ARCHITECTURE

One of the most frequently adopted models to realize autonomic systems is the MAPE-K model [3], which basically consists of a control loop with 4 phases - **M**onitor, **A**nalyze, **P**lan, **E**xecute - in continuous interaction with a **K**nowledge base (See Figure 2).

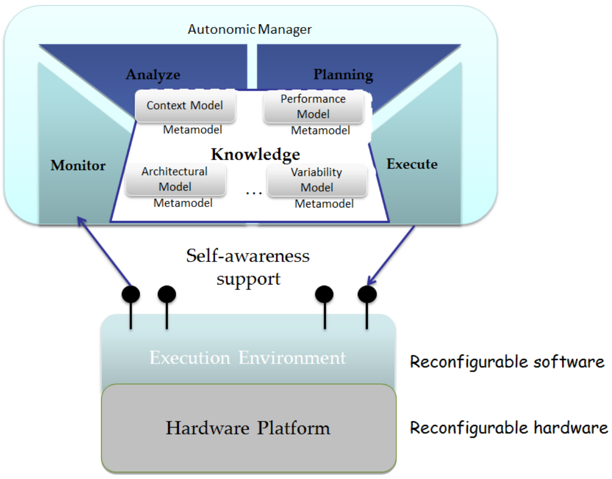

Figure 2. Self-awareness: monitor, analyze, plan, execute

Monitoring phase concerns continuous monitoring of different properties of managed elements (e.g., CPS devices such as sensors, actuators, gateways; CPS services; physical environment). Either the managed elements can proactively provide the management information to the autonomic managers or it can respond passively to explicit requests of the manager. The main research challenge for this phase in CPS is how to collect data in such large-scale networks of heterogeneous devices and how to pre-process it and meaningfully store it according to what they represent. In fact, significant research has been done on collecting data from sensor networks. However, the focus has initially been on monitoring sensor measurements that are used in various smart applications. The management information (e.g., network, device and environmental parameters, performance metrics) should also be included in the collected data. Generic and extensible semantic-based data models for management information are to be defined. The lifecycle of sensed data and data freshness will also need to be monitored, managed and somehow stored with the data to enable relevant and up-to-date (i.e. performing as expected by the user) CPS applications. Additionally, monitored data will need also to be related to user/application preferences/requirements and acquired in a context-sensitive manner as part of the data acquisition process.

In the *Analysis* phase, collected "raw" data are processed and analyzed in order to obtain valuable information on the state of the managed elements. This information is used to keep the up-to-date state information about the managed elements. In CPS, the main research challenge rises for the scalability and response time. Huge amounts of data are to be generated from a great number of devices for CPS applications in real-time. Autonomic property is based on reactivity. The analysis should thus be done in quasi real-time. The appropriate semantic based categorization of the collected information in dynamically changing storage compartments will greatly reduce data-mining and associated analysis execution times. Contrarily to the traditional "off-line" data processing techniques, stream data management systems, complex-event-processing mechanisms and pattern-detection techniques in real time should be used. In order to avoid excessive data transmission, local analysis on devices should be preferred when possible.

Given the situation and context information obtained from the analysis phase, the *planning* phase gives decisions for actions to take in order to attain the high-level objectives defined by human administrators. Decisions can be done conforming to, for instance, event condition rules, objective functions, or prediction models based on techniques such as Bayesian networks, decision trees or fuzzy logic. In the CPS context, the highly dynamic environments and the continuous, real-time nature of CPS applications bring new challenges to handle, such as prediction models at run-time, real-time conflict management between rules, and learning from experience with case-based reasoning. In addition, giving the right decision with limited computing resources is a complex task. Tight interactions with control and artificial intelligence communities are necessary to explore and adapt existing techniques to the CPS domain.

According to the decisions taken in the planning phase, *execution* phase schedules and executes the decided actions on the managed element. They mainly consist of re-configuration actions in order to obtain the state desired by the autonomic manager. The most common actions are modifications of device, network or performance parameters, and installation, update or uninstallation of software modules and firmware. In highly distributed environments such as CPS, the overall consistency should be maintained. Actions should thus guarantee transactional properties such as atomicity, isolation or durability, with several consistency degrees that would let the manager to choose the best trade-off between the resource consumption and the consistency degree.

Applying the MAPE-K model in cyber-physical systems necessitates adequate computing infrastructures. Service-oriented architecture (SOA) is one candidate technology that offers primitives for creating modular, reconfigurable and extensible software platforms. Service-based approach allows composing flexible, robust and adaptable applications from platform services and base services developed by different city stakeholders such as telecom operators, service providers or device manufacturers. Next section gives some examples of such middleware services.

IV. SERVICE ORIENTED MIDDLEWARE FOR SELF-AWARE CYBER-PHYSICAL SYSTEMS

Two independently growing sets of enabling technologies that have great potential of helping cities to be smarter have emerged, namely cyber-physical systems (CPS) and cloud computing. On the one hand CPS can sense the real-world and act on it, thus providing context-awareness to applications, on the other hand cloud computing can store and process this data with additional properties such as scalability near to infinity, reliability and elasticity.

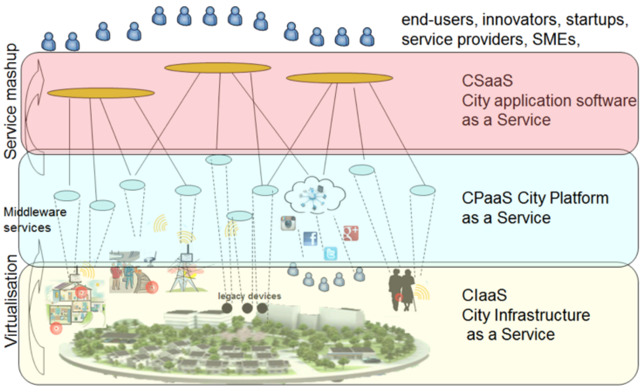

Figure 3. Cloud model for CPS services

Cloud computing provides indeed a flexible virtual execution environment for processing any application over a potentially infinite number of resources, scaling up and down accordingly to usage behaviours [4]. Its decentralized and service-oriented nature enables high reliability and accessibility to modular information from anywhere at anytime. Cloud centers can provide an on-demand metered service at different granularities with a requested quality of service level. Besides new technological enablers, Cloud paradigm brings new economical models based on the pay-per-use that reduce initial investments and related operational costs to the actual use of service, the cost and time for new service providers, in particular for SMEs, to enter to a wide market with a minimum infrastructure management requirements. They can thus experiment with novel and innovative services whilst reducing the risk of wasting resources.

Figure 3 shows the Architectural layers of the City Infrastructure, based on the typical cloud stratification. At the bottom the City Infrastructure (CIaaS), a set of interconnected physical resources all made homogenous using virtualisation technologies. The CIaaS exposes virtualised resources (e.g., sensors and actuators) by mean of a set of open standard APIs that will enable the seamless access to any device, data, and computational power. The Platform layer (CPaaS) consists on a set of specialised middleware services that enable specifically the mash-up and development of applications for the citizens (end users) and the city Manager (administrators). The CSaaS is represented by a number of sample applications developed using the CPaaS and CIaaS APIs and running over the cloud on any user device (smart phones, tablets, PCs, etc.). These smart city applications would validate both the design and specification of the APIs, and they represent an initial step toward the Smart City Ecosystem.

This paper is particularly interested in the platform layer - aka middleware layer - that aims at bringing the self-awareness to the smart city infrastructures. It is based on a distributed service-oriented approach for integrated management of heterogeneous devices in smart city ecosystems based on the CPS general architecture given in the section III. The middleware provides a generic set of services on monitoring the city data, processing the data, planning and executing adequate actions identified by the applications such as smart metering for utilities (electric, gas, water); traffic monitoring; air quality monitoring; waste management; etc.

The main components of this middleware are described in the following subsections.

A. Data collection and processing services

This component collects data from various heterogeneous devices and processes them against queries defined in a declarative language. The mechanism is implemented based on a formalized query and data model, as well as on techniques of distributed processing of data streams coming from sensor devices [5] [6]. Figure 4 shows the working behavior of data collection and processing.

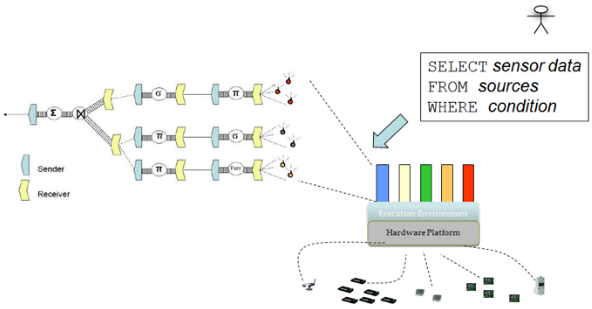

Figure 4. Data collection and processing services

B. Composition and mash-up of sensor and actuator services

The coordination of sensors and actuators is handled using a service composition approach. Devices export their functionalities in terms of services. Application creation thus consists of composing these services and to obtain higher level composed services. We provide tools to assist developers to create with a model-based approach to guarantee robustness, correctness and self-adaptation properties. Figure 5 gives an overview schema for this coordination.

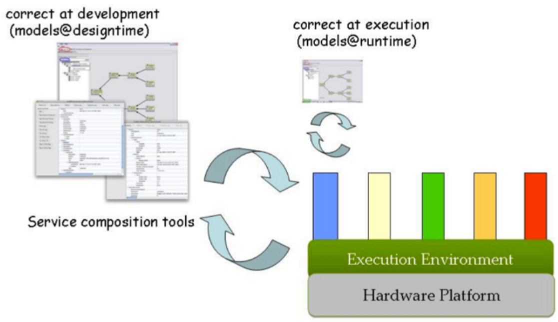

Figure 5. Coordination of sensor and actuator services

C. Device management services

Another middleware service that we provide is the device/service management service. With an extensible management information model we propose to different city actors a management mechanism to perform various operations such as Software/Firmware management, configuration management and performance management [7] [8]. Figure 6 illustrates the management services.

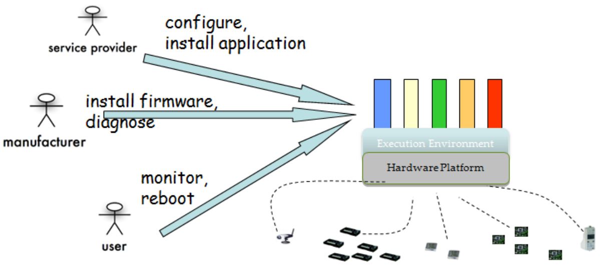

Figure 6. Device management services

D. *Autonomic management services*

Following the MAPE model presented in the section III we provide an autonomic life cycle management for smart city applications, from development until runtime changes [9] [10]. The middleware provides a domain specific specification language based on the notion of components to define the architecture of pervasive applications. These components are developed using generic services provided by the middleware. Then at runtime, an application manager takes this description and configures a service oriented execution platform in order to deploy and start the application, all taking into account current state of the environment, represented by several runtime models. And while the application is running, this manager continues to monitor and self-manage the created application by taking into account the context changes, not only in the system execution environment but also in the physical world. Figure 7 illustrates this service.

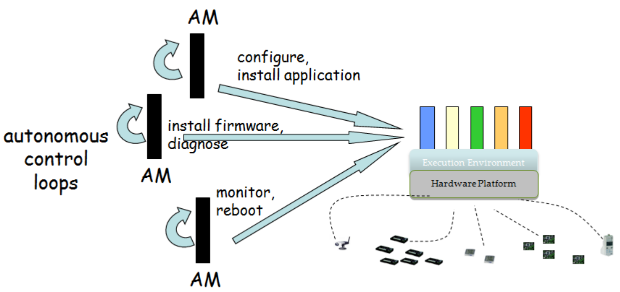

Figure 7. Autonomic management services

V. Conclusion & Recommendations

This paper highlighted the importance of "self-awareness" in the cyber-physical systems that will provide the major enables for new generation smart cities. It has given some research challenges in self-aware CPS domain and has introduced its own vision on service oriented smart city infrastructures. It presented a middleware that can help building reliable smart city applications by reusing several middleware services.

In addition, given the above-mentioned challenges, we propose the following recommendations to progress towards self-manageable CPS systems:

- Already existing fundamental research results from domains including artificial intelligence, biological systems, control theory, embedded systems and software engineering are necessary to build scientifically-proven, solid, robust and reliable solutions. It may be necessary to tailor existing research to the CPS context. In addition, plural-disciplinary conferences and workshops should be organized to foster the interaction level between experts in those domains.

- Novel methodologies, architectures, algorithms, technologies, and protocols should be developed taking into account CPS-specific characteristics such as resource constraints, dynamic, un-predictive, error prone and lossy environments, distributed and real-time data handling and decision-making requirements, etc. Characterization of self-x properties in CPS context should be done based on real-life cross-domain use cases.

- Autonomic issues should be considered from the very early phases of CPS system implementations, from conception to deployment of devices, infrastructures and services. The self-awareness property should be injected to any software module, however separated from the functional code. Hardware should also be designed to be reconfigurable.

- Devices should either be able to provide management data to autonomic managers, or to have embedded intelligence to reason and act locally. Automated tools for development, deployment, and supervision of CPS devices and services should be developed.

- Prototypes should be developed at early stages in order to validate the theoretical results by measuring the overhead that autonomy can bring to CPS systems.

- CPS is expected to be composed of very heterogeneous networks, thus standard interfaces should be defined for interoperability. Specific working groups on self-management issues should be created in standardization organizations, industrial alliances. A self-organizing network (SON) for LTE of 3GPP is a good initiative that should be followed by other next generation networks standards.

- Model-driven approaches are solid ways to provide correctness, robustness, reliability, and dependability properties, and they have already proven their importance for the conception and development of embedded systems. In the context of CPS, they should be extended to obtain these properties not only at design and development time but also at deployment and run-time for self-adaptation.

- New modes of interaction with autonomic CPS systems that would increase the quality of experience of users are necessary, e.g., user assistance with intuitive multimodal interfaces: to monitor and control autonomic systems, to define rules and policies, and to receive important feedback in real-time.

- Various stakeholders (users, manufacturers, integrators, service providers, telecom operators, etc.) will be dynamically and concurrently involved in CPS systems;

particular attention should thus be paid for resource sharing and policy conflict resolution between different actors. In addition to many existing concepts from the distributed systems domain, fundamentals of economics can also be applied to resolve these issues.

- New programming paradigms should be proposed for creating self-aware applications with the ability of self-adaption on-the-fly. The flexibility, dynamicity, modularity of the service-oriented approach (SOA) is particularly interesting. An integration of SOA with new device-oriented approaches can be useful for programming cyber-physical environments.

- Security and privacy issues should be considered very seriously since CPS deals not only with huge amount of sensitive data (personal data, business data, etc.) but also has the power of influencing the physical environment with its control abilities. Cyber-physical environments must thus be protected from any kind of malicious attacks.

- In order to make the smart objects paradigm come true (meant here are objects with perception capabilities, embedded intelligence and high level of autonomy and communication) a lot of research is needed in order to fit sensors/actuators, CPU, memory, energy, etc. into tiny chips. The challenge is quite high, assuming that autonomy requires complex algorithms which themselves require high CPU power and therefore also a comfortable amount of available energy.

ACKNOWLEDGMENT

This research work was partially supported by the European FP7 projects, BUTLER (www.iot-butler.eu) and IoT-i (www.iot-i.eu).

REFERENCES

[1] Uexküll, Jakob. Shaping our future: Creating the World Future Council. Foxhole, Devon, United Kingdom. UNT Digital Library. http://digital.library.unt.edu/ark:/67531/metadc13722/. Accessed November 14, 2012.

[2] Autonomic Computing: IBM's perspective on the state of Information Technology. 2001. http://www.research.ibm.com/autonomic/manifesto/autonomic_computing.pdf

[3] An architectural blueprint for autonomic computing. IBM White paper. June 2005

[4] The future of Cloud Computing, Opportunities for European Cloud Computing beyond 2010 Online: cordis.europa.eu/fp7/ict/ssai/events-20100126-cloud-computing_en.html.

[5] Levent Gürgen, Claudia Roncancio, Cyril Labbé, André Bottaro, Vincent Olive. SStreaMWare: A service oriented middleware for heterogeneous sensor data management. In International Conference on Pervasive Services, ICPS (2008)

[6] Levent Gürgen, Cyril Labbé, Claudia Roncancio, and Vincent Olive. SStreaM: A model for representing sensor data and sensor queries. In Proceedings of the International Conference on Intelligent Systems And Computing: Theory And Applications (ISYC), July 2006, Cyprus.

[7] Levent Gürgen, Johan Nyström-Persson, Amin Cherbal, Cyril Labbé, Claudia Roncancio, Shinichi Honiden. Service-oriented middleware for dynamic management of heterogeneous sensing devices. In Proceedings of the 7th ACM International Conference on Pervasive Services (ICPS'10). July 2010. Berlin, Germany.

[8] Levent Gürgen and Shinichi Honiden. An integrated management middleware for networked sensing systems.In Pervasive 2009. May 2009. Nara, Japan.

[9] Levent Gürgen, Amin Cherbal, Rémi Sharrock and Shinichi Honiden. Autonomic management of heterogeneous sensing devices with ECA rules. In proceedings of the IEEE ICC 2011 Workshop on Embedding the Real World into the Future Internet (RWFI 2011). June 2011.

[10] O. Gunalp, L. Gurgen, V.Lestideau, P. Lalanda. Autonomic Pervasive Applications Driven by Abstract Specifications. Proceedings of the 2012 international workshop on Self-aware Internet of Things, in conjunction with ICAC 2012. 978-1-4503-1753-5. Pages 19-24. 2012