Research Plan, ETH Zurich

Architecting a Web of Things for Real-World Applications.

Ph.D. candidate: Dominique Guinard
Advisor: Friedemann Mattern

Employment start date: June 2007
Ph.D. enrollment date: December 2008
Proposal submission date: April 2009

Distributed Systems Group
Institute for Pervasive Computing
ETH Zürich

1 Summary

In spite of the increasing popularity of open source communities, progress in networked objects is still being limited by the lack of clear, standardized, and interoperable communication protocols. For the realm of the "Internet of Things" to materialize (and be scalable), there is an unmet need for a common and open architecture that can be used to access and interact with several embedded devices. The Internet is a good example of a global network of computers that interoperate together in spite of the large amount of different software and hardware platforms available, and there is a growing number of embedded devices that can connect directly to the Internet.

With the recent developments in the embedded Web, Internet of Things projects are evolving towards Web connectivity of embbeded computers populating the physical world. Based on these observations, our first contribution is an architecture blending smart things, i.e. sensor and actuator networks, embedded devices, appliances and everyday digitally (RFID, barcodes) enhanced objects with the Web. We want to consider smart things as first class citizens of the Web. Thus, we propose to leverage the existing and ubiquitous Web protocols as common ground where embedded devices could

interact with each other. In particular we would like to explore and evaluate how the REST architectural style [1] can be applied to smart things. One of the advantages of using these Web patterns is that popular Web tools and techniques (e.g. browsers, search engines, caching systems), languages (e.g, HTML, JavaScript, PHP, Ruby on Rails, etc.) and interaction techniques (e.g. browsing, linking, bookmarking) can be directly applied to the real-world.

Our goal is to contribute to a distributed deployement (also known as "ecosystem") of smart things which people can use to build distributed applications upon using well-accepted languages and tools. Building on the growing popularity of Web 2.0 services and in particular Web mashups [2], we would like to introduce an architecture and tools that enable the creation of "physical mashups" using services from the Web of today and tomorrow's Web of Things.

2 Introduction

A central concern in the area of pervasive computing has been the integration of digital artifacts with the physical world. In particular, the "Internet of Things" has essentially explored the development of applications built upon various networked physical objects [3]. Embedded devices of the physical world are still mostly disconnected from the Web and form a myriad of small incompatible islands. Increasingly, embedded devices and consumer electronics as for example the Chumby, Gumstix, Nabaztag or digital picture frames, get Internet connectivity but cannot be controlled and monitored without using dedicated software and proprietary interfaces. As a consequence, smart things are hard to integrate into composite applications.

The core contribution of this work is to explore the applications and architectural challenges towards the realization of a flexible ecosystem of devices that can be reused serendipitously first by developers and then by end-users. We focus on composite applications of the Web of today and tomorrow's Web of Things. Just as tech-savvy users create Web mashups by combining several Web resources [2] we would like to enable them to create "physical mashups" by composing virtual and physical service on the Web.

Our first contribution in this field is to propose a Web-oriented architecture which should serve as a "universal" API (Application Programming Interface) for smart things. We would like to create a Web of Things by making smart things first-class citizens of the Web. We position the Web of Things as an refinement of the Internet of Things by integrating smart things not only to the Internet (i.e. to the network), but also to the Web (i.e. to the application layer).

To achieve this goal, we want to re-use and adapt patterns commonly used on the Web. First, by embedding Web servers on smart things and applying the REST architectural style [1, 4] to the physical world. The essence of REST is to focus on creating loosely coupled services on the Web so that they can be easily reused [5]. REST is actually core to the Web and uses URIs for encapsulating and identifying services on the Web. In its Web implementation it also uses HTTP as a true application protocol. It finally decouples services from their presentation and provides mechanisms for clients to select the best possible formats. As a consequence of the proposed architecture smart things and their functionality get transportable URIs that one can exchange, reference on Web sites and bookmark. Things are then also linked together enabling discovery simply by browsing. The interaction with smart things can also almost entirely happen from the browser, a tool that is ubiquitously available and that most of the people understand well [6]. Furthermore, smart things can benefit from the mechanisms that made the Web scalable and successful such as caching, load-balancing, indexing and searching.

Nevertheless, REST was meant as a software architecture for distributing hypermedia and thus is not directly transposable to the world of smart things. As a consequence, in the first part of this thesis, we will propose extensions and methods to apply these patterns to smart things. In particular we will evaluate them when applied to sensor and actuator networks, mobile phones and RFID tagged objects. Finally, we want to compare the RESTful architecture with alternatives such as DPWS (Device Profile for Web Services) and traditional WS-* services.

Although applying a RESTful architecture to the Web of Things is an important step towards integrating smart things, it still needs further extensions on which we want to work. An important one is to support service description, which is a key feature for usability and sharing. At first we would like to explore a crawling approach where services offered by smart things are discovered by crawling (machine) or browsing (human) the things' HTML pages. This method has worked fine for search engines for years and is the way most RESTful APIs are still described (e.g. the del.icio.us REST-like API[1]), thus we would like to see how it applies to smart things. Nevertheless, crawling non-structured documents might also lead to irrelevant and non-compliant descriptions. Uses cases considering semi-automated machine to machine communication (for example a sensor communicating with some actuators) would particularly be affected by this procedure and requires more standardized expressive descriptors. We suggest exploring the use of Microformats[2] and other "lightweight" semantic languages (e.g. RDFa) to annotate human-oriented Web pages with key information encoded in a machine-readable format. Microformats have recently been used for describing RESTful services [7]. We would like to experiment how to use a similar approach for describing resources on smart things.

Enabling a mashable Web of Things requires a mechanism to share smart things through their RESTful API. For example, one could share the temperature sensors in a house with the community. However, this is a complex mechanism since these devices are part of our everyday life and their public sharing might result in serious privacy violations. This

[1] `http://delicious.com/help/api`
[2] `http://microformats.org`

aspect is rarely tackled in the Web of Things (or Internet of Things) related literature. HTTP already provides authentication mechanisms (e.g. HTTP Authentication[3]) based on credentials and server-side groups. While this solution is already available for free on most (embedded) Web servers, it presents a number of drawbacks. First, when considering a large number of smart things it becomes quite unmanageable to share credentials for each of them. Then, as the shared resources are not advertised anywhere, sharing also requires the use of secondary (sometimes unsafe) channels such as sending emails containing the credentials to people we want to share with.

We would like to leverage existing social structures to allow sharing of things, and for that we propose building upon social networks (e.g. Facebook, Linkedin, Twitter, etc.) and their (open) APIs. Using social networks enables users to share things with people they know (e.g. relatives, friends, colleagues, fellow researchers, etc.), without needing to recreate yet another social network from scratch. Additionally, this enables advertising and sharing through a unique channel: you can tell your friends about the smart things you shared with them directly by posting messages to their profile.

3 State-of-the-Art

Linking the Web and physical objects is not a new idea. Early approaches started by attaching physical tokens (such as barcodes) to objects to direct the user to pages on the Web containing information about the objects [8, 9]. These pages were first served by static Web Servers on mainframes, then by early gateway system that enabled low-power devices to be part of wider networks [10]. The key idea of these work was to provide a virtual counterpart of the physical objects on the Web. URIs to Web pages were scanned by users e.g. using mobile devices and directed them to online representation of real things (e.g. containing status of appliances on HTML pages or user manuals). With advances in computing technology, tiny Web servers could be embedded in most devices [11, 12]. The Cooltown project pioneered this area of the physical Web by associating pages and URIs to people, places and things [6] and implementing scenarios where this information could by physically discovered by scanning infrared tags in the environment. We would like to go a step further and to propose an architecture to truly make smart things part of the Web so that they can not only serve data but also be actuated and controlled from the Web.

A number of projects proposed solutions to expose the functionality of smart things in order to build applications upon. Among them, the now classical systems are CORBA, JINI, or RMI and UPnP. The advent of WS-* Web Services (SOAP, WSDL, etc.) led to a number of work towards deploying them of embedded devices and sensor networks [13, 14]. While helping towards the integration to enterprise applications, these solutions are often too heavy for devices with limited capabilities [15], do not directly expose the smart

[3] http://www.ietf.org/rfc/rfc2617.txt

things' functionality on the Web as RESTful architectures do and are not truly loosely-coupled [5]. Several systems for integration of sensor systems with the Internet have been proposed — for example SenseWeb [16] and Pachube[4] — which offer a platform for people to share their sensory readings using Web services to transmit data onto a central server. Unlike the Web of Things, these approaches are based on a centralized repository and devices are considered as passive actors only able to push data.

One of the first mentions of a Web of Things composed of RESTful smart things comes from [17]. However it focuses mainly on the discovery of devices and not on how to provide their functionality on the Web. Closer to the work we envision is [18] and in particular [19]. They consider the use of REST-like architectures for sensor networks. We build upon these approaches and propose a systematic implementation of the RESTful constraints [4]. We do not focus on the lower sensors level but explore the applications from a Web view-point. For this, we propose a framework for semantically describing smart things based on Microformats. In these terms we build upon projects for describing RESTful resources like [7] but focus on describing smart things rather than virtual services. We want to allow creating a Web of Things that is accessible for people to develop on top of smart things. This should occur in a similary manner to what they do when building Web 2.0 mashups [20]. We would like to enable "physical mashups" [21].

Finally, we believe that having a comprehensive and useable sharing mechanism for things is key to the user acceptance and wide deployment of the Web of Things. Several platforms such as SenseWeb [22] or Pachube propose a central platform for people to share their sensor data. However, these approaches are based on a centralized data repository and use proprietary ACLs (Access Control Lists). A promissing solution would be to leverage existing social structures to allow sharing of things, and for that we build upon social networks (e.g. Facebook, Linkedin, Twitter, etc.) and their (open) APIs. The SenseShare project [23] goes towards this direction as it allows users to share sensor data with their friends. It also allows owners to apply different filters to the data before sharing it. However, similarly to Pachube, SenseShare acts as a datastore between the sensors and the clients. It allows sharing the data coming from sensors but does not support direct interactions with the devices. Furthermore, SenseShare uses Facebook only as social network. Such a tight coupling with a single external service whose contract (API and allowed accesses) is subject to change over time, is problematic. Indeed, We want to support different social networks, and enable users to control which one to use for each device.

4 Goals of Thesis

The main goal of this thesis is to explore the architecture and tools necessary to build a distributed deployement of smart things which fosters serendipitous re-use of smart

[4] `http://www.pachube.com`

things to create opportunistic applications [20], i.e. composite applications easily created by re-using existing services or devices. Just as people create Web mashups involving Web and Web 2.0 services, they should be able to create “physical mashups” mixing services from the real and virtual worlds together. A key point is to consider physical mashups beyond the desktop metaphor by seeing how these can be built in-situe for instance by using mobile devices as composition devices. In particular, we want to explore three aspects:

4.1 A Web Oriented Architecture for a Composable Ecosystem of Smart Things

Research Question: *“What are the important constraints and design patterns to enable loosely-coupled integration of things to the Web?”* In this first part we would like to propose a Web-oriented architecture for smart things. We want to apply Web patterns such as the REST architectural pattern and Web syndication (e.g. the Atom protocol) to sensors and actuator networks, embedded devices and RFID tagged objects. In particular, we will implement prototypes of devices providing a RESTful API either directly or indirectly (through reverse-proxies). We will then evaluate these Web-enabled devices in terms of performances and ease of integration to new applications such as mashups. For this purpose we will deploy a Web of Things testbed. Finally, we will compare our proposed architectures with alternatives such as the use of WS-* Web Services. For this, we will leverage our experience with smart things integration through DPWS Services at SAP Research [24].

4.2 Discovering and Sharing Things

Research Question: *“In a global Web of Things, how can smart things be discovered and shared towards re-usability of their services?”* In the second part we want to explore the Ambient Findability [25] and discovery [26] of smart things first by annotating them. These annotations should enhance and integrate well with the existing Web (e.g. by embedding it in HTML pages). They should support users in creating mashups by describing the resources they can compose in terms of expected outputs and inputs. It is worth noting that our goal is not to create new languages but rather to understand how existing and emerging languages such as HTML Microdata[5] or Microformats[6]. Likewise, service discovery and semantics are research topics on their own and we do not pretend providing a comprehensive solution to these problems. We would rather take a exploratory approach to see how existing research in these fields could be re-used on a Web scale.

[5] http://www.w3.org/TR/microdata/
[6] http://microformats.org/

Furthermore, we will consider other Web-based techniques for easing the discovery of things such as extending user search queries based on related keywords extracted from services on the Web (e.g. Wikipedia, Yahoo Web Search, etc.) [27]. These service discovery techniques will be evaluated both in quantitative (how well do they perform?) and qualitative (is the technique really helping users to find smart things?) terms. For this we will use the proposed techniques to describe the devices of the testbed.

A key point to discover smart things and use them in mashups is that their resources should be shared. Thus, we would like to propose an architecture that enables smart things to be easily shared on the Web. For this we will implement a prototype leveraging existing social networks and their open APIs to allow sharing smart things amongst friends, relatives and colleagues. This prototype is going to be evaluated to share the smart things deployed in our testbed.

4.3 Empowering End-Users to Mashup the Real-World

Research Question: *"How can we empower end-users to build upon an ecosystem of Web-enabled smart things"* The final goal of the thesis is to experiment how the other parts help towards a truly composable distributed deployement of smart things. To explore this we propose three levels of physical mashups: mashups for developers, mashups for domain experts and mashup editors for end-users. We will illustrate these levels with one prototype for each. For the last level (i.e. mashup editors for end-users) we will also propose a software framework that offers basic constructs (e.g. aggregators, parsers, widget assistants, screen-scrapers) which can be used to build mashup editors [2] on top of a Web of Things. We will use this framework to create two prototypes of mashup editors one for a mobile platform, another for a desktop environment.

5 Detailed Work Plan

The workpackages of this thesis are directly drawn from the goals:

1. **A Web Oriented Architecture for a Composable Ecosystem of Smart Things.**
Duration: 12 months. This workpackage contains an exploration of the different systems for integrating smart things to the Web. It finally proposes an architecture (and several prototypes implementations) on which the following workpackages are built.

2. **Discovering and Sharing Things.**
Duration: 10 month. In this workpackage we propose new models for discovering things on the Web and sharing their functionality.

3. **Empowering End-Users to Mashup the Real-World.**
   Duration: 10 months. In this last workpackage we implement tools to bring the concept of the two other workpackages to developers and then end-users.

6 Progress to Date

6.1 Web of Things Architecture

This workpackage is in its finalization phase. We began our work by looking at deploying WS-* Web Services on embedded devices and connecting them to enterprise software [14]. We then worked on Web-enabling sensor nodes [15] using a RESTful architecture and proposed a system federating both RESTful and WS-* services for things in [28]. In [29] we implemented Web proxies for Smart Meters. From this we derived the concept of Smart Gateways in [28] and [30]. In [31] we introduced the Web of Things architecture which we further described in [32].

After having worked on the architecture and the Web-enablement of wireless sensor networks and smart meters we now look into Web-enabling tagged objects. For this purpose we currently develop a RESTful component for the EPCglobal Network [33] called RESTful EPCIS.

6.2 Discovering and Sharing Things

In order to foster the discovery of smart things on the Web, we began by proposing and evaluating a system for searching for networked smart things described in [27, 28]. For this workpackage we also work on lightweight semantic descriptions for smart things. We began by creating RDFa vocabularies and are now evaluating the use of Microformats and HTML 5 Microdata.

As mentionned before, we would like to support discovery through sharing. For this we developed a sharing and service advertising platform making use of social networks [34] and are currently in the process of evaluating it.

6.3 Empowering End-Users to Mashup the Real-World

In this last workpackage we concretely illustrate the proposed architectural concepts by showing how it eases the creation of physical mashups for developers, domain experts and end-users. With the Energy Visible project [29, 31, 35] we have shown how Web developers can directly leverage from the WoT architecture in order to create an energy monitoring and control interface. For domain experts, we have just finished working on a Web dashboard on top of the RESTful EPCIS that managers can use and extend in order to give them an overview of the life-cycle of each tagged product. Eventually, for end-users we created a software framework [36] to support several physical mashup editors. We used it to implement a mobile mashup editor on Android and a desktop mashup editor using the clickscript visual programming language [32].

7 Time Schedule

Workpackage	Start	End	Currently done
WP 1	Dec 2008	Dec 2009	100%
WP 2	Dec 2009	Dec 2010	70%
WP 3	Dec 2009	Mar 2011	70%
Writing	Dec 2010	May - June 2011	5%

References

[1] Fielding, R.T.: Architectural Styles and the Design of Network-based Software Architectures. PhD thesis, University of California, Irvine (2000)

[2] Yu, J., Benatallah, B., Casati, F., Daniel, F.: Understanding mashup development. IEEE Internet Computing **12**(5) (2008) 44–52

[3] Fleisch, E., Mattern, F.: Das Internet der Dinge. Springer (July 2005)

[4] Richardson, L., Ruby, S.: RESTful Web Services. O'Reilly Media, Inc. (May 2007)

[5] Pautasso, C., Wilde, E.: Why is the web loosely coupled? a Multi-Faceted metric for service design. In: Proc. of the 18th International World Wide Web Conference (WWW2009), Madrid, Spain (April 2009)

[6] Kindberg, T., Barton, J., Morgan, J., Becker, G., Caswell, D., Debaty, P., Gopal, G., Frid, M., Krishnan, V., Morris, H., Schettino, J., Serra, B., Spasojevic, M.: People, places, things: web presence for the real world. Mob. Netw. Appl. **7**(5) (2002) 365–376

[7] Kopecky, J., Gomadam, K., Vitvar, T.: hRESTS: an HTML microformat for describing RESTful web services. In: Proc. of the 2008 IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology - Volume 01, IEEE Computer Society (2008) 619–625

[8] Roy, W., Kenneth, F., Anuj, G., Beverly, H.: Bridging physical and virtual worlds with electronic tags. In: CHI '99: Proceedings of the SIGCHI conference on Human factors in computing systems, New York, NY, USA, ACM (1999) 370–377

[9] Ljungstrand, P., Redström, J., Holmquist, L.E.: Webstickers: using physical tokens to access, manage and share bookmarks to the web. In: DARE '00: Proceedings of DARE 2000 on designing augmented reality environments, New York, NY, USA, ACM (2000) 23–31

[10] Schramm, P., Naroska, E., Resch, P., Platte, J., Linde, H.: Integration of limited servers into pervasive computing environments using dynamic gateway services. Technical Report 0202, Computer Engineering Institute, University Dortmund, Germany (2002)

[11] Duquennoy, S., Grimaud, G., Vandewalle, J.: The web of things: interconnecting devices with high usability and performance. In: Proc of the 6th IEEE International Conference on Embedded Software and Systems (ICESS'09), HangZhou, Zhejiang, China (May 2009)

[12] Hui, J., Culler, D.: Extending IP to low-power, wireless personal area networks. Internet Computing, IEEE **12**(4) (2008) 37–45

[13] Priyantha, N.B., Kansal, A., Goraczko, M., Zhao, F.: Tiny web services: design and implementation of interoperable and evolvable sensor networks. In: Proc. of the 6th ACM conference on embedded network sensor systems, Raleigh, NC, USA, ACM (2008) 253–266

[14] de Souza, L.M.S., Spiess, P., Guinard, D., Koehler, M., Karnouskos, S., Savio, D.: SOCRADES: a web service based shop floor integration infrastructure. In Floerkemeier, C., Langheinrich, M., Fleisch, E., Mattern, F., Sarma, S.E., eds.: Proceedings of the Internet of Things. First International Conference, IOT 2008, Springer (March 2008)

[15] Guinard, D., Trifa, V., Pham, T., Liechti, O.: Towards physical mashups in the web of things. In: Proc. of the 6th International Conference on Networked Sensing Systems (INSS), Pittsburgh, USA (June 2009)

[16] Luo, L., Kansal, A., Nath, S., Zhao, F.: Sharing and exploring sensor streams over geocentric interfaces. In: Proceedings of the 16th ACM SIGSPATIAL international conference on advances in geographic information systems, Irvine, California, ACM (2008) 1–10

[17] Stirbu, V.: Towards a RESTful plug and play experience in the web of things. In: Semantic Computing, 2008 IEEE International Conference on. (2008) 512–517

[18] Luckenbach, T., Gober, P., Arbanowski, S., Kotsopoulos, A., Kim, K.: TinyREST - a protocol for integrating sensor networks into the internet. In: Proc. of the Workshop on Real-World Wireless Sensor Network: SICS, Stockholm, Sweden (2005)

[19] Drytkiewicz, W., Radusch, I., Arbanowski, S., Popescu-Zeletin, R.: pREST: a REST-based protocol for pervasive systems. In: Mobile Ad-hoc and Sensor Systems, 2004 IEEE International Conference on. (2004) 340–348

[20] Hartmann, B., Doorley, S., Klemmer, S.: Hacking, mashing, gluing: Understanding opportunistic design. Pervasive Computing, IEEE **7**(3) (2008) 46–54

[21] Wilde, E.: Putting things to REST. Technical Report UCB iSchool Report 2007-015, School of Information, UC Berkeley (November 2007)

[22] Kansal, A., Nath, S., Liu, J., Zhao, F.: SenseWeb: an infrastructure for shared sensing. IEEE Multimedia **14**(4) (2007) 8–13

[23] Schmid, T., Srivastava, M.B.: Exploiting social networks for sensor data sharing with SenseShare (October 2007)

[24] Spiess, P., Karnouskos, S., Guinard, D., Savio, D., Baecker, O., de Souza, L.M.S., Trifa, V.: SOA-based integration of the internet of things in enterprise services. In: Proc. of the IEEE International Conference on Web Services (ICWS 2009), Los Angeles, California, USA (July 2009)

[25] Morville, P.: Ambient Findability. O'Reilly Media (October 2005)

[26] Edwards, W.K., Newman, M.W., Sedivy, J.Z., Smith, T.F.: Experiences with recombinant computing: Exploring ad hoc interoperability in evolving digital networks. ACM Trans. Comput.-Hum. Interact. **16**(1) (2009) 1–44

[27] Guinard, D., Trifa, V., Spiess, P., Dober, B., Karnouskos, S.: Discovery and on-demand provisionning of real-world web services. In: Proc. the IEEE International Conference on Web Services (ICWS 2009), Los Angeles, California, USA (July 2009)

[28] Guinard, D., Trifa, V., Karnouskos, S., Spiess, P., Savio, D.: Interacting with the SOA-based internet of things: Discovery, query, selection, and On-Demand provisioning of web services. IEEE Transactions on Services Computing **99**(PrePrints) (February 2010)

[29] Guinard, D., Weiss, M., Trifa, V.: Are you energy-efficient? Sense it on the web! In: Adjunct Proceedings of Pervasive 2009 (International Conference on Pervasive Computing), Nara, Japan (May 2009)

[30] Trifa, V., Wieland, S., Guinard, D., Bohnert, T.M.: Design and implementation of a gateway for web-based interaction and management of embedded devices. In: Proc. of the 2nd International Workshop on Sensor Network Engineering (IWSNE 09), Marina del Rey, CA, USA (June 2009)

[31] Guinard, D., Trifa, V.: Towards the Web of Things: Web Mashups for Embedded Devices. In: 2nd Workshop on Mashups, Enterprise Mashups and Lightweight Composition on the Web (MEM 2009), Madrid, Spain (April 2009)

[32] Guinard, D., Trifa, V., Wilde, E.: Architecting a mashable open world wide web of things. Technical report, ETH Zurich (2010)

[33] Floerkemeier, C., Lampe, M., Roduner, C.: Facilitating RFID development with the accada prototyping platform. In: Proceedings of the Fifth IEEE International Conference on Pervasive Computing and Communications Workshops, IEEE Computer Society (2007) 495–500

[34] Guinard, D., Fischer, M., Trifa, V.: Sharing using social networks in a composable web of things. In: Proceedings of the 1st IEEE International Workshop on the Web of Things (WoT 2010) at IEEE PerCom 2010, Mannheim, Germany (March 2010)

[35] Weiss, M., Guinard, D., Staake, T., Roediger, W.: eMeter: an interactive energy monitor. In: Adjunct Proceedings of Ubicomp 2009 (International Conference on Ubiquitous Computing), Orlando, Florida, USA (September 2009)

[36] Kovatsch, M., Weiss, M., Guinard, D.: Embedding internet technologies for home automation. In: Submitted