Closing the Loop for Interactive Architecture

Internet of Things, Cloud Computing, and Wearables

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Interactive architecture occurs in buildings when part of the building engages in exchange of information with the user, in such a way that the interactive system adjusts it's assumptions about the user's needs and desires. Acquiring the user's needs and desires is no trivial task. Currently there are no techniques that will reliably make such assertions. Building a system that unobtrusively monitors the inhabitant seems to be a tall order, and making the system ask the user all the time is very distracting for the user. An alternative option has become available however: personal wearables are increasingly monitoring the user. Therefore it suffices that the interactive system of the building gets in touch with those wearables, rather than duplicating the sensing function of the wearables. The enabling technology for wearables is Internet of Things, which connects physical objects (smart objects) on a virtual level, and Cloud Computing, which provides a scalable storage environment for wearables and smart objects. In this paper we outline the implications of the convergence of these three technologies in the light of interactive architecture.

Keywords: *Interactive architecture, Internet of things, Wearables, Cloud computing*

INTRODUCTION

In this paper we investigate a number of technologies through the lens of interactive architecture. In earlier work we developed a framework for the design of interactive architecture (Achten 2014a; Achten 2014b; Achten 2013). Interactive architecture occurs in buildings when part of the building engages in a dialogue with the user. The dialogue should not be taken as a literal conversation between the building and the user (although it might take that form), but means rather an exchange of information and actions between the user and the building that have some meaning for both the building and the user. Meaning for the user usually is straightforward - it can vary from utilitarian (switching on/off lights, controlling the heating, managing shades, and so on) to leisure (watching television, setting music, managing ambient levels, and so on). The term "meaning" for the building is a bit less obvious, as we cannot attribute to the building a level of understanding similar to people. In the current discussion it is sufficient to speak of meaning when the action and information exchange leads to a different state of the managing system that enables the interactivity of the building. The managing system has an internal representation of the user's needs and desires, and uses this to steer its own behaviour. From this we derived that something has meaning to the building whenever the system adjusts it's assumptions about the user's needs and desires.

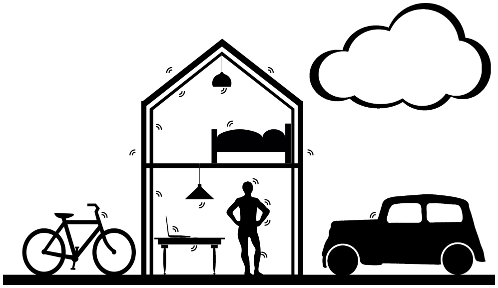

Figure 1
The building, Internet of Things, Wearables, and Cloud computing constitute an interactive ecology.

Interaction in a building can amount to many different things. In any sophisticated system we would require a minimum of necessary user interactions to accommodate the needs of the user. Ideally, the interaction should be as unobtrusive or ubiquitous as possible (Weiser 1999). This puts quite a large burden on the interpretation capacities of the interactive system. It means the system has to observe the user and infer their current or (near) future needs. Computer vision and movement sensors are able to sense the environment and the user, but robust and reliable algorithms for inferring user needs do not exist to our knowledge. A building needs some level of self-understanding, for example in a representation of its own context, structure, components, systems, and processes (Mahdavi 2005). In research on domestic and office robots, semantic maps are proposed on top of metric and topological maps. These semantic maps contain functional information of spaces (kitchen, work place, etc.) and objects (furniture) (Sheng et al. 2015), which is sufficient for robots but not for user needs understanding. Automated user needs understanding is still on a theoretical level, for example concerning social emotional information (Esposito et al. 2015). There are some computer vision techniques which are capable to analyse human behaviour, but they apply only in very restricted environments and contexts (Chaaraoui et al. 2012).

The main hypothesis in this paper is that part of the burden to detect and infer user needs can be transferred to three fairly recent technological developments which are still in early stage (Figure 1):

- Internet of Things.
- Wearable technology.
- Cloud Computing.

The *Internet of Things* aims to build computational representations of physical objects so that they can be manipulated by virtual entities. For interactive architecture it means that a lot of intelligence and knowledge about location and state of things is transferred to the objects themselves, and needs no longer be inferred top-down.

Wearables are simple or more advanced sensing and computing devices that people wear on their body. They often have GPS functionality and track user vital statistics such as heart rate, respiration, caloric burning, and so on. For interactive architecture wearables form a middle layer that can inform an interactive system about the physical condition of the user.

Cloud computing is a comprehensive set of servers and network technologies that are outsourced and scale with user's needs, meaning transfer of data and computing resources from locally managed systems to network-based services. For interactive architecture it is relevant because the interactive system may obtain necessary data from the Cloud and it may use computational facilities from Cloud services - reducing the need for large capacity facilities in the building

In the remainder of this paper, we describe the technologies, and bring them together into a framework for interactive architecture.

Internet of Things

The *Internet of Things* (*IoT*) is a recent development. As such, there is no general consensus yet about the exact meaning (Atzori et al. 2010). The term was most likely originally coined by Kevin Ashton in 1999 (Ashton 2009). *IoT* is a very much an umbrella term, under which more research areas are located such as such as *Cyber-Physical Systems* (Salim and Haque 2015), *Embedded Intelligence* (Guo, Zhang and Wang 2011), or *Hybrid Products* (Knutsen et al. 2011).

In the most general sense, *IoT* means that the Internet space, which currently consists of connected computers (virtual systems), is expanded to include physical objects. These physical objects have computational representations that through the Internet can interact with other objects or computers. In most cases these objects (also known as "*smart objects*") are small ubiquitous devices such as sensors, actuators, RFID tags, smart phones and embedded systems (Petroulakis et al. 2013).

Increasingly connected versions of *IoT* are *Web of Things* (*WoT*), and *Social Web of Things* (*SWoT*) (Mashal et al. 2015). *SWoT* sees an increasing activity of smart objects posting on social websites (Atzori et al. 2014). Integration with social websites is an enabler for higher acceptation and usage of *IoT* because of the low threshold of social media. Businesses again build on this through participative marketing (Jara et al. 2014).

The wide variety of objects requires the development of protocols that can be accessed by devices ranging from very low capabilities (for example RFID tags) to high capacities (for example smartphones) (Gama et al. 2012). Initiatives such as *6LoWPAN* (*IPv6 over Low-power Personal Area Networks*) aim to integrate sensors directly into the IP protocol (Atzori et al. 2010; Mashal et al. 2015). (Miorandi et al. 2012) state that the inclusion of objects in the Internet is not just an extension, but necessitates a fundamental rethinking what an object is in the context of *IoT*. Their list of requirements (physical embodiment, communication functionalities, unique identifier, name and address, computing capabilities, and means to sense physical phenomena) is close to understanding of agents or agency, and may actually include people (although they do not claim this).

Search in *IoT* cannot use standard approaches that are based on keywords, because smart objects are located in the physical world and in many cases are also moving; additionally the user also is dynamic. To overcome this problem, (Römer et al. 2010) developed *Dyser*, a search engine which can find dynamic objects on the Internet. Another approach is to search by themes through vertical searching engines (Zhao et al. 2015). Location information by itself is not sufficient to anticipate future actions of a system. (Jin et al. 2013) propose a so-called *composite subscription language* that can capture spatio-temporal events which can then be used to reason about future actions. (Jara et al. 2014) discuss *Digcovery*, a mechanism for global resource discovery, device access for deployed smart objects, and sensors and devices from end users in the context of Smart Cities. Another aspect improving search and speeding up interaction with smart objects is storing individual history of a smart object - so-called *digital object memory* (Barthel et al. 2013).

Many smart objects only have very limited resources in terms of memory, processing power, energy, and communication channels. Therefore, they are also very limited in terms of security measures that they can apply. It is clear that *IoT* remains only a promise if security is not solved in a robust and realistic way (Roman, Najera and Lopez 2011; Saied et al. 2014; Sicari et al. 2015). (Erguler 2014) notes potential weaknesses in RFID-based solutions that may lead to security breaches when compromised readers are used. Security and privacy are not only technological issues but also social and legal (Weber 2010), requiring accepted social roles and legal frameworks. It is also necessary to consider the economic aspects for business in order to make *IoT* feasible. (Lee and Lee 2015) identify three major categories for enterprise applications: *monitoring and control* (including smart buildings), *big data and business analytics*, and *information sharing and collabora-*

tion. Business actors in these areas will develop their own applications, some of which will find their way into buildings as well.

Smart objects connected to *IoT* are embedded in the world, where they may respond to events in the world or through communication with other objects or actors. This means that an event (dangerous situations, social event, or other occurrences) may trigger activation of a large amount of smart objects within a particular area which may lead to overload of communication channels. Control strategies usually applies for human-to-human communication fall short because they do not count on such massive communication. Therefore, different control strategies are required that lessen the potential load, for example *FASA* proposed by (Wu et al. 2013). (Asimakopoulou et al. 2013) suggest that on-the-fly creation of so-called *micro-clouds* with smart objects such as smart phones outperform centralized systems in emergency situations. (Guo et al. 2013) discuss opportunistic *IoT*, which are conglomerations of networking devices (typically smartphones and smart vehicles) not relying on existing infrastructure but using short-range radio techniques. (Du and Zhu 2012) propose a framework to apply *IoT* technology for urban early warning systems. (Yang et al. 2013) investigate the potential of *IoT* to enhance emergency response operations, in particular concerning three rhythms: *mobilization*, *preliminary situation assessment*, and *intervention*. These findings are integrated in an *ERIS* (*Emergency Response Information System*) and was assessed in the UK. They found that *IoT* offers benefits to accountability of resources and personnel, assessment of the situation, resource allocation, and multi-organizational coordination.

For interactive architecture, IoT offers the technological infrastructure to embed the many and diverse sensors applications and communication requirements of these devices in the building.

Wearables

Wearable technology integrates computational and sensing functionality into objects that we wear close on our body. These can be more or less traditional objects such as glasses, gloves, rings, armbands, and watches, but also integrated into fabrics such as shirts, trousers, and coats. Usually wearable technology is said to have started in the 1980'ies with the introduction of the wrist-watch with calculator or the "computer in a backpack" invented by Steve Mann (Sultan 2015). Strictly speaking watches, smartphones, and Personal Digital Assistants (PDA) such as tablets are not wearable technology, but we will consider them in this category. In particular smartphones and tablets feature a wide range of sensor types combined with communication facilties. (Daponte et al. 2013) list for example: *microphone*, *infrared port*, *GPS receiver*, *WAP browser*, *CMOS/Dual camera*, *Bluetooth*, *Wi-Fi*, *Proximity sensor*, *accelerometer*, *digital compass*, *gyroscope*, *Near Field Communication*, and *barometer*.

Most contemporary wearable technology developments take place in the area of health-care and fitness. Agent-based applications for fitness motivation have been around since early 2000 (*Virtual Coach* by IJsselsteijn et al. 2004), followed a bit later by wearable technology (*SensVest* by Knight et al. 2005). (Buttussi and Chittaro 2008) developed *MOPET*, a wearable system for physical fitness training. (Lee and Chung 2009) present a *Smart Shirt*, which monitors heart rate, ECG, and acceleration. (Lenzi et al. 2011) developed a thin contact layer between skin and wearable robot (for application of elbow active orthosis) that measures stress and controls the therapy session for the patient. (Domingo 2012) identifies strong potential in the linkage between wearables, smart objects, and *IoT* to assist disabled people for example with activities such as shopping, learning, and domestic situations. *Google Glass*, an Augmented Reality eyewear prototype developed by Google (2011-2015) has been used in various pilot projects in health-care (Sultan 2015). (Vidal et al. 2012) found that wearable eye-tracking (using different technologies than Google Glass) may be an unobtrusive technology for monitoring mental disorders. (Lim et al. 2011) present a wearable plaster system that wirelessly captures arm motion for stroke patient recovery analysis. (Steele and Lo 2013) see a particular benefit of wearables for telehealth in rural and remote areas that do not have access to high-bandwidth facilities. (Santos et al. 2015) developed a *Constrained Application Protocol* that can link up Personal Health Devices to IoT. (Ogunduyile, Olugbara and Lall 2013) report on a *Wearable Ubiquitous Healthcare System* targeted to monitor elderly people. Developing and designing proper wearable products lacks a proper ergonomic foundation (Lin and Kreifeldt 2001; Luximon et al. 2012), resulting many attempts to produce wearables that are technology-pushed but not user-based (Knutsen et al. 2011).

Wearables form a rich information source concerning the state of inhabitants in the built environment. An interactive system needs to query the wearables in order to obtain much information that otherwise would be very difficult to infer.

Cloud Computing

Cloud computing is a comprehensive set of servers and network technologies "...to outsource IT activities to one or more third parties that have rich pools of resources to meet organization needs easily and efficiently" (Hassan 2011). They are the next generation follow-up of late 1990íes *Clusters* and early 2000's *Grids*. Cloud computing features novel architectures and virtualisation techniques. It enables transfer of data and computing resources from locally managed systems to network-based services. Originally Cloud computing was a business model and technological solution for enterprises, without *IoT* in mind. The main benefits are flexibility in demand and reducing in-house expertise on storage, processing, safety, and security of the data management process. (Buyya et al. 2009) state that computing will one day become one of the essential utilities (next to water, electricity, gas, and telephony) for people. As not everyone can afford powerful individual machines such as PC's or laptops, they see the solution for this in Cloud access (Broberg et al. 2009).

The properties of Cloud computing are not only beneficial for business and people, but they align very well with requirements of storage and processing power in *IoT* which makes it a clear candidate to connect with *IoT*. (Gubbi et al. 2013) note that Cloud computing offers a reliable service which has the capacity to store, process, and visualise the massive amount of data generated through *IoT* (Gubbi et al. 2013). (Garg et al. 2013) offer a series of metric and ranking system to compare commercially available Cloud solutions.

Micro-clouds (Sotitiadis et al. 2013) are proposed as relatively closed pool of cooperating devices and their resources that form smart environments. Typically a micro-cloud services a particular functional area (house, office, industrial building, etc.). The authors also developed a protocol for collaborating micro-clouds in the case that advances can be gained by combining resources of nearby objects (apartments in a high-rise for example).

For interactive architecture Cloud computing offers the background capacity for wearables and smart objects in the *IoT* to store data, access processing power, and stay updated on dynamic and moving objects and people.

Convergence to architecture

Applying *IoT*, *wearables*, and *Cloud computing* in architecture to buildings sets a number of boundary conditions which simplify the application of the technologies:

- **Location**: buildings are precisely localised, therefore their services are localised as well. Inhabitants are either present in the building (direct interaction), or in a different place (requiring agency of the building services). Public location-based services can breach privacy (they gather information about place and interest of a user; (Niu et al. 2015), but this is less the case in the home/occupant relationship.
- **Characteristics**: (Gubba et al. 2013) note the following characteristics for Smart Home-/Office application: small network size, few

users (family members), rechargeable batteries power source, Wifi, 3G, 4G LTE backbone Internet connectivity, local server, RFID and WSN devices, and small bandwidth requirements.
- **Easier orchestration of services**: the amount of smart objects and services which have to coordinate their tasks in a building context is much less and also more specific than in the general *IoT* context. (Colistra et al. 2014) demonstrate that a consensus protocol reaches a percentage error of 5% with respect to the optimal allocation obtainable with a centralized approach.

A number of applications of one or more of the above technologies are in progress or have been concluded. (Watson et al. 2004) report on an experiment with five commercial buildings (supermarket, bank office, government office, offices and cafeteria, and university library), in which *Machine-to-Machine* (*M2M*) technology was used to autonomously make the buildings reduce electric demand based on fluctuating energy prices posted on the Internet. (Fantacci et al. 2014) propose a *M2M Gateway* architecture which they apply in Telecom Italia Lab offices. The architecture is aimed to provide maximum flexibility for the user, independent of the network operator. (Torriti 2014) reports a 5.2% better energy demand reduction achieved by smart objects compared to preset load controllers. (Ventura and Baldassari 2014) experiment with a methodology to generate interactive and connected smart objects. (Kleiminger et al. 2014) report on home-occupancy predicting algorithms for smart heating. Depending on isolation quality and occupation ratios, annual energy savings ranged from 6% for well-isolated much occupied buildings to 17% for poorly isolated buildings. (Calderoni et al. 2012) discuss the "*around me*" application, which provides localised information in a city environment - this was prototyped and tested in Cesena, Italy. The *SmartSantander* project uses the city of Santander, Spain, to provide and test smart services such as *environmental monitoring*, *parking management* and *driver guidance*, *parks and gardens irrigation*, *augmented reality*, and *participatory sensing* (Sanchez et al. 2014).

The majority of work on these novel technologies are obviously technology-pushed, as they are still in early development - Cloud computing being the most mature of the three. In their study on urban indicators, city benchmarking, and real-time dashboards, (Kitchin et al. 2015) warn against a naïve-instrumental interpretation of data generated by such systems. As they say, the data capture is designed, negotiated, and debated and in consequence, interpretation and action are normative, political, and ethical processes. This applies to cities and to a lesser degree in buildings as well.

For the embedding in buildings, RFID tags currently seem to be the most robust candidate. The technology is mature and well-developed (Mitton and Simplot-Ryl 2011). To increase device lifetime by better assessing sleeping times for Bluetooth devices, (Collotta and Pau 2015) demonstrate a fuzzy approach which increases device operational lifetime by 30%. For Wi-Fi based devices, (Bovet and Hennebert 2013) report a 2-6% energy demand reduction using a hybrid layer that selects the most appropriate communication protocol. They note that gains increase with the amount of people using such devices at the same time.

Closing the loop for interactive architecture

IoT, *wearables*, and *Cloud computing*, together with other sensors in the building provide the technological layer for interactive architecture. The data that is generated through this layer needs to be interpreted by the controller component of the interactive system. Guo, Zhang and Wang (2011) distinguish between three different kinds of inferences: *individual intelligence* (understanding inhabitants), *spatial intelligence* (understanding the immediate environment of inhabitants), and *social intelligence* (understanding community dynamics). All these three aspects need to be covered in an interactive system in order to create sensible interactions. Because of their immediate bearing on daily surroundings, development of smart environment requires a robust and reliable development method to avoid costly (or worse) mistakes in the operation of the environment. Formal programming methods such a *π-calculus* may provide such a basis (Lekshmy and Bhaskar 2015).

It has to be noted that an interactive system most likely is not a completely closed system. New components have to be introduced to an existing system and be able to link up in the local ecology, and users should also be able to fairly easily add their own functionality (for example using *Raspberry Pi* - Vujović and Maksimović 2015). For this purpose easy to use platforms that takes care of these possibilities have to be provided as well (Guinard et al. 2011; García et al. 2014; Mayer et al. 2014; Mashal et al. 2015) such as *Midgar*, *Cooltown*, *SenseWeb*, *Xively*, *SensorBase*, and so on. In addition, (Shin 2014) argues that *IoT* developments should be considered from a socio-technical viewpoint, not just a technology-driven one. *IoT* should be localized, not "one size fits all," which operates under the assumption that user should adapt rather than technology. In the context of Korea, he suggest that IoT literacy programs are required, a constant debate should be fostered, social demands should not be dictated by the market alone, and users have to be empowered to utilize IoT technology for themselves.

CONCLUSION

From the above discussion, we believe that it is clear that the convergence of the three technologies of *IoT*, *wearables*, and *Cloud computing* will have a major impact on architecture. First of all, it will significantly help the establishment of interactive architecture. Second, this trend is so powerful that even without professional consideration by architects of these technologies, these technologies will merge anyway and change architecture. It is critically important for architects and researchers to be informed of these developments and to assess its impact on architecture and on the profession of architecture.

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