Reflecting on the Ambient Intelligence Vision
A Cyber-Physical-Social Perspective

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Abstract: By acquiring and reasoning about user and environmental context, Ambient Intelligence (AmI) systems enable intelligent and intuitive interactions between people and their physical environments. AmI traditionally seeks to build on ubiquitous sensing technologies and communications to acheive this aim. Over a decade later, people are frequently immersed in or engaged with alternative, software, environments, such as those provided as web applications or social networks. Now, to form more complete contextual representations of users, AmI solutions require the context of multiple environments in which users may be immersed. This paper proposes a middleware supported framework for cyber-physical-social AmI that relies on the combined efforts of modern web technologies and ubiquitous computing as the enabling technologies.

1 INTRODUCTION

In a modern data-saturated world, knowledge and inference-driven systems integrate intelligence into real-time services and devices allowing for the provision of diverse, self-adaptive, autonomous, personalised and intelligent computing applications (Weiser, 1991). This is the vision of ubiquitous computing research which aims to provide unobtrusive deployments of technology enabling the provision of Ambient Intelligent (AmI) solutions. AmI (Sadri, 2011) enables autonomous environments and, specifically, intuitive interaction through the provision of Intelligent User Interfaces (IUIs) enabled by in-situ intelligence and embedded decision making.

While Wireless Sensor Network (WSN) and associated middleware research focuses on enabling this goal, the World Wide Web (WWW) has become a modern day source of personal and informative, real time and archival data. Through user participation in social networks and use of personalised web services, the social web (Chi, 2008) has become an extension of people's everyday lives. Social and non-social web sites provide real time reports of topical information, breaking news and environmental information such as weather reports and regional disaster alerts. Furthermore, virtual and augmented reality research is beginning to enable real-time interactions with environments that are very different to the physical world we live in.

Acknowledging these advances in technology requires us to extend our understanding of context, environments and sensors. The enabling technologies for AmI must now accommodate modern environments and leverage advances in WWW research. Further, the implications of bridging the cyber-physical-social divide must be assessed so as not to limit user adoption of cyber-physical-social AmI solutions.

This paper summarises advances in Ubiquitous Computing and the evolution of the World Wide Web (Section 2). We then reflect on the traditional AmI vision (Section 3), offering a current perspective on what we consider *context*, *environment*s and *sensors*, and addressing the benefits and challenges of cyber-physical-social AmI. This analysis motivates our proposed middleware-supported framework for cyber-physical-social AmI, which composes existing research efforts into a unified architecture (Section 4). Conclusions and a research agenda are offered to deliver the foundations of cyber-physical-social AmI (Section 5).

2 THE WORLD WIDE WEB AND UBIQUITOUS COMPUTING

The World Wide Web and Ubiquitous Computing are diverse yet converging areas of research, both of

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which strive to produce personalised and intelligent solutions that will be adopted by and meet the needs of users. This section provides an overview of state of the art research in these areas followed by analysis of the supporting frameworks that contribute to our unified research agenda.

2.1 World Wide Web

Since the birth of the World Wide Web (WWW) in 1990 it has been transformed from a web of documents to a web of interconnected information, users and services (Web 2.0). The emergence and wide spread adoption of social networks in particular has embedded users into the web by providing a mechanism through which they can connect and share. By providing programmatic access to data through standardised interfaces, this social web facilitates the web of services, enabling enhanced and personalised applications which further enhancing a user's web-based experience.

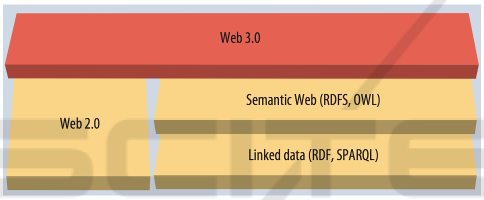

Figure 1: Semantic Web 3.0. (Hendler, 2009).

In 2009, Hendler proposed that Web 3.0 will be in part the realisation of the semantic web (Hendler, 2009) as outlined by Tim Berner's Lee in 2001 (Berners-Lee et al., 2001). It is stated that Web 3.0 can be viewed as "Semantic Web technologies integrated into, or powering, large-scale Web applications". This is illustrated in Figure 1 which identifies the underlying semantic technologies that link Web 2.0 data allowing the formation of a Semantic Web upon which Web 3.0 applications will strive. Web 3.0 applications differ from those we know to be Web 2.0 in that they will become 'smarter' due to the ease of performing simple inferences with the support of semantic knowledge bases.

In 2010, Hendler and Berners-Lee (Hendler and Berners-Lee, 2010) argued that the social connected nature of current web systems is an early realisation of web connected social machines that will achieve much more through collaborative functionalities. It is argued that the future web must "be designed to allow the virtually unlimited interaction of the Web of people". It is envisioned that people will build and share their own social machines.

While social machines have not yet been realised, Web 2.0 persists in the mainstream and Web 3.0 applications are beginning to emerge in the research literature (Hendler, 2009). Initial insights into Web 4.0 and beyond are now offered in research literature. Aghaei (Aghaei et al., 2012) and Kambil (Kambil, 2008) speculate, independently, on what is to come after Web 3.0, agreeing that Web 4.0 will be a realisation of the WWW where intelligent interactions between humans and machines take place. Kambil offers further insights into Web 5.0, proposing a sensory-emotive web, a WWW that is responsive to users emotional state or receptivity to specific information.

2.2 Ubiquitous Computing

Ubiquitous computing involves building highly responsive and self-adaptive systems which aim to increase the integration of technology into the fabric of everyday living (Weiser, 1991), for example, smart spaces and environmental monitoring. Enabling this vision requires the availability and use of heterogeneous sensing devices that enable data to be captured in real time. AmI by its very nature requires that sensors and services be unobtrusive to a user, necessitating the provision of sensors that can be embedded in the environment and existing user devices is essential.

Smart spaces aim to provide ubiquitous (hidden) services such as ambient personalised displays, mood lighting, and automated services by embedding intelligence in devices within a utilised space such as a home or office. Internet of Things (IoT) and Wireless Sensor Network (WSN) researchers aim to enable smart spaces through small to medium size deployments of smart things and sensors within an occupied space.

Environmental monitoring systems typically gather a diverse range of data relating to the conditions of an environment enabling the development of intelligent ecosystems that react to diverse phenomena such as pollution, wildlife migration, natural disaster or intrusion. Such systems require large scale WSNs that can be left in the environment unattended for long periods of time, meaning the provision of sensing devices capable of intelligence is required. The solution offered by the Sensor Web is "web accessible sensor networks and archived sensor data that can be accessed and discovered using standard protocols and Application Programming Interfaces (APIs)" (Botts et al., 2008).

Internet of Things (IoT), Web of Things (WoT) and Sensor Web are terms often given conflicting definitions. Some IoT definitions (Atzori et al., 2010) focus on internet enabled devices, while others emphasise the networking capability of such devices, not unlike the WSN's that underpin Sensor Web research. This seems a natural progression from the IoT vision that started in the RFID community where internet enabled devices are limited in computational capabilities. IoT researchers have since begun experimenting with more powerful devices or smart objects that are capable of inter-device communication amongst other capabilities such as semantic reasoning and actuation. Web of Things (WoT) research, which is seen as the next stage of the IoT, focusses on use of emerging Web Standards to facilitate reuse of internet enabled devices. The Sensor Web (Delin, 2002) paradigm envisions connectivity of entities and users in real and web-based environments through the adoption of large scale heterogeneous sensor-actuator networks.

Such networks support intelligent sensing and actuating sometimes through the embedding of agents (Tynan et al., 2005) sometimes even advocating Autonomic Wireless Sensor Networks (Marsh et al., 2004). They treat all entities as equal citizens regardless of their origin, form or nature (O'Hare et al., 2012). While IoT enabled applications described in research tend to be 'local', such as smart spaces, Sensor Web researchers strive to solve 'global' problems such as environmental monitoring and early warning systems.

2.3 Supporting Frameworks

Middleware and programming frameworks aim to ease the process of developing and deploying systems that typically compete for resources and are dependent on complex underlying technologies. While the two terms are often used interchangably within research literature, here we provide a distinction. Middleware frameworks ease and manage the deployment of underlying technologies that enable data access and management, and also facilitate application deployment and access to resources. Programming frameworks enable rapid development of user-facing prototypes and applications through the provision of API's that enable abstracted access to the data managed by the middleware. An end-to-end support framework comprises both middleware and programming technologies. Each of WWW, IoT, WSN, and SensorWeb research domains employ such supporting frameworks to allow developers of user facing solutions to remain application domain experts, without concern for the underlying infrastructure upon which their application runs.

Given the nature of the current WWW, which can be described as Web 2.0, a Social Web, and a Web of Services, Service Oriented Architectures (SOA) have become widely adopted as the supporting framework for Web application developers (Issarny et al., 2011). Service Oriented Middleware for the WWW usually focuses on service discovery and composition (Milanovic and Malek, 2004) while programming support is typically provided through mashup tools that allow developers use mutliple diverse services within a single application through an easy to use interface (Grammel and Storey, 2010). Cloud Computing infrastructures have emerged as a powerful tool for supporting rapid deployment of services and applications (Armbrust et al., 2010).

Middleware and programming frameworks for ubiquitous computing aim to ease the process of deploying, potentially large scale, WSNs, enabling developers to build data-driven solutions without the learning curve involved with network deployment and programming. There is a wealth of middleware research in the broad ubiquitous computing and WSN domains (Raychoudhury et al., 2013) (Wang et al., 2008) (Hadim and Nader, 2006), much of which provides solutions to distinct problems in specific domains, or only supports the use of homogenous sensors. A generalised middleware for inherently heterogeneous environments was called for in 2001 (Geihs, 2001); over a decade later, it has still not been realised. Due to the flexibility it offers in terms of reusability, extensibility and interoperability of services, SOA is becomming a standard approach for developing middleware solutions for the Internet of Things, WSN and Sensor Web research (Mohamed and Al-Jaroodi, 2011) (Chu and Buyya, 2007). SOA partially overcomes the heterogeinity problem bringing middleware researchers closer to realising a generic middleware solution for diverse systems.

3 REFLECTING ON THE AmI VISION

Many of the developments described in the previous sections have occurred within the last decade. In the case of AmI, the question arises as to what are the implications for paradigm itself and how or if it should reinvent itself in light of these developments. While the challenges of WWW and ubiquitous computing research differ, research and developments into the supporting frameworks for such systems are converging towards common, SOA, solutions and a single unifying framework is expected to emerge. The divide between WWW (cyber-social) and ubiquitous computing (physical-social) will be bridged, enabling a platform for cyber-physical-social AmI solutions. Bridging the cyber-physical-social divide is of benefit to the AmI paradigm. How it is accomplished must be accommodating of the users that will adopt AmI technologies and are core to the success of AmI research. Here we discuss cyber-physical-social context, environments and sensors and explore both the benefits and challenges of bridging the cyber-physical-social divide within the context of AmI research.

3.1 Cyber-Physical-Social Context, Environments and Sensors

Context comprises any information that characterizes the situation of any person, place, or object that is considered relevant to the interaction between a user and an application (Abowd et al., 1999). For AmI, context is typically aquired through deployments of ubiquitous sensing technologies monitoring users, their immediate physical environment and the things they interact with. In keeping with this definition of context, cyber-physical-social AmI requires a broader understanding of environments and sensors.

An environment can be considered to be the geographical location and immediate surroundings within which a user or entity currently resides or equally the cyber (web-based/software) environment that a user or entity is engaged with or immersed in. Modern AmI users are increasingly likely to be immersed in environments alternative to the one they are physically present in, such as social networks, games, e-commerce, and virtual/augmented reality. This must be accommodated by a sensing infrastructure enabling cyber-physical-social AmI.

While sensors are typically defined by the features of the device that enable it to sense, here we refocus on the capabilities regardless of the form of the sensor. A cyber sensor is a software sensor that monitors any programmatically accessible environment, user or entity (O'Grady et al., 2013). A sensor that is intelligent, as distinct from operating continuously in a *sense-transmit* cycle, can monitor its own state and that of connected sensors. It can also decide when it is appropriate to report a phenomenon, reducing communication cost which can have a significant impact on the operational lifespan of a battery-powered sensor, or reducing traffic to a server which is being queried by a cyber sensor. A supporting infrastructure for cyber-physical-social AmI must treat cyber sensors and physical sensing devices as equal citizens.

3.2 Cyber-Physical-Social AmI: Challenges and Benefits

A core challenge for AmI has traditionally been user adoption of AmI solutions. The importance of intuitive interaction is as important now as it was when Weiser proposed the original ubiquitous computing vision, yet remains a distant goal. In the case of AmI, if the emphasis on the physical element, that is ubiquitous computing, is augmented with a social perspective, this may inform the behaviour of AmI systems and make them more human-centric. Cyber-physical-social AmI solutions will be based on a more complete contextual foundation of its users than the knowledge base achievable through embedded sensors alone. Difficulties in assessing a user's mood or motivations will be addressed through the inclusion of a user's real time social web presence within the solution.

The traditional vision of calm computing encompasses technologies that stay hidden and make decisions without any user input. Motivated by human ability to exploit their environments, Rogers (Rogers, 2006) describes an alternative goal to Weiser's calm computing that is *engaging computing*, shifting from 'proactive computing' to supporting 'proactive people'. It is also argued that we "simply don't do 'smart' well yet" (Greenfield, 2006), but perhaps that is because we don't have access to comprehensive historical data for individual users such that a system may learn to adapt appropriately. It is proposed here that the provision of engaging technologies is a necessary step in the journey to ultimately providing calm computing. As users become more engaged with (and accepting of) technology, they will learn to understand and trust in technological advances. Simultaneously, researchers will learn what users are willing to accept from technology, both in terms of what tasks/decisions they are willing to hand over to automated solutions and what level of control users demand over their own data. This intermediate step between engaging and calm computing will facilitate the organic growth of large user annotated data sets (aggregated through user interactions with technology), providing a new historical knowledge base upon which local, personalised, intelligent solutions can become automated to suit AmI users.

While it is envisaged that middleware will bridge the cyber-physical-social divide for AmI solutions, it must be considered how that middleware will operate. While services exist that facilitate the sharing of WSN, or Internet of Things, data to the web, the publication of private sensor data to an external data broker will lead to concerns surrounding user privacy and ownership of data. The idea that all user information, including that originating from sensors embedded in private environments, is managed by third party data brokers goes against modern social expectations and will lead to resistance in terms of adopting these new technologies. Advances in information retrieval, dissemination and capture technologies far exceed those in areas of web data providence and privacy. A contributor of information to the current WWW must understand the privacy controls of hugely diverse service providers whose terms and conditions may change at any point. Relying on these external data brokers to control and secure information means users cannot be certain of who has access to their information and for what purpose. It is therefore necessary when bridging the cyber-physical-social divide, to provide a safe place where information processing and intelligent decision making can take place while adhering to user defined privacy requirements. This results in the requirement for web-based data to be integrated with WSN data within a local distributed middleware that supports fully customisable privacy and security solutions. Such an approach will facilitate fusion of widely diverse user data, integrating WWW, Sensor Web and IoT research efforts to date, as proposed in the following section.

4 PROPOSED CYBER-PHYSICAL-SOCIAL ENABLEMENT FOR AmI

In Section 2, Service Oriented Architecture (SOA) was identified as a common approach to enabling WWW, IoT and Sensor Web solutions. Despite the differences between WWW and ubiquitous computing, a mapping can be made between the challenges to be addressed by services, enabling a unifying solution to bridge the cyber-physical-social divide. An adaptation of a layered SOA architecture for cyber-physical-social enablement is described as follows (adapted from (Atzori et al., 2010)):

Objects. Sensors, Smart devices, WSNs, Targeted aspects of any software including WWW sites and services

Object Abstraction. Software the unifies access to and control of objects regardless of original form, converting sensed data to a standardised format

Service Management. Software services that provides features to simplify deployment and management of a complete infrastructure, e.g., standards, object discovery, configuration and status monitoring. Trust, privacy and security, if not inbuilt to the core of the middleware architecure, are typically provided as services that can be configured as required

Service Composition. Supports the application developer in composing applications supported by the infrastructure through the composition of predefined services exposed through an API

Applications. Multiple, concurrent appplications competing for infrastructure resources in a way that is managed by the previous layers according to its configuration

A supporting framework for cyber-physical-social AmI will accommodate semantic reasoning and diverse artificial intelligence solutions (Murdoch and Nixon, 2010) enabling the development of engaging AmI solutions through which user feedback will support enhancement of automated services and more intuitive interactions.

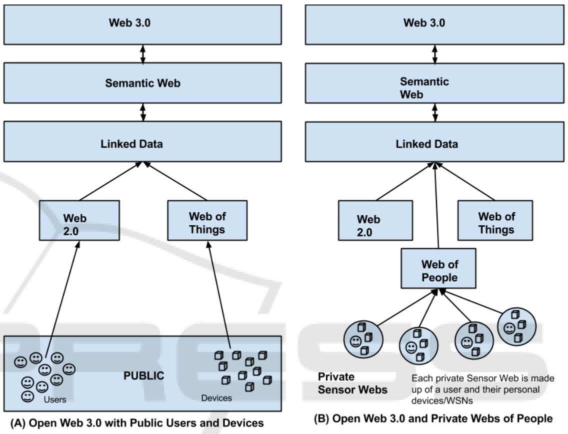

Figure 2: (A) Open Web 3.0 and Web of Things (B) Private Webs of People co-existing with Open Web 3.0.

To further understand the requirements of an enabling framework for cyber-physical-social AmI, we consider the wider perspective, how IoT, Sensor Web and WWW research agendas will unify to acheive this goal. In Section 2 we identified current and projected future trends in WWW research. In Figure 2 (A) we extend Figure 1 to illustrate how the Web of Things integrates physical sensor data in a manner that is separate to the user contributed information obtained via Web 2.0. This separation of concerns is not a true representation of the reality which involves interactions between people and things resulting in production of data. A Web of People enabled by social machines is an innovative vision that has the potential to unlock a realm of previously unimaginable personalised applications and services. However, the notion of an open social web and the current architecture of web technologies is in conflict with the necessity to provide user friendly yet highly granular customisable privacy controls.

The open WWW will only contain information that is contributed with the intention of being open and reused. We propose that the answer is not exclusively in finding better privacy solutions but in understanding how, why and when to use the open WWW. Then, we need to facilitate the evolution of personal social machines that are created from the ground up. People will be empowered to be their own data broker, privacy rules for individual pieces of data will travel with that data as it is shared/disseminated through networks of users. Data that is not deemed public will not be shared to the open web. In Figure 2 (B) we extend the Web 3.0 framework to allow for personal sensor webs, enabling a web of people. A sensor web is a collection of sensors, in this case, monitoring all entities relating to a particular user and their environment. A private sensor web comprises a user, their devices, their personal environments, and information about their connections and connected environments to which the users have been granted mutual access. It is proposed that a private sensor web will be the enabling technology for personal social machines with fine grained user control over privacy and organically grown connections between users supported by distributed mobile social networks. The separation of concerns between private user information and that shared publicly via Web 2.0 and the Web of Things will allow for bespoke privacy mechanisms that are user controlled, while the open web remains unthreatened.

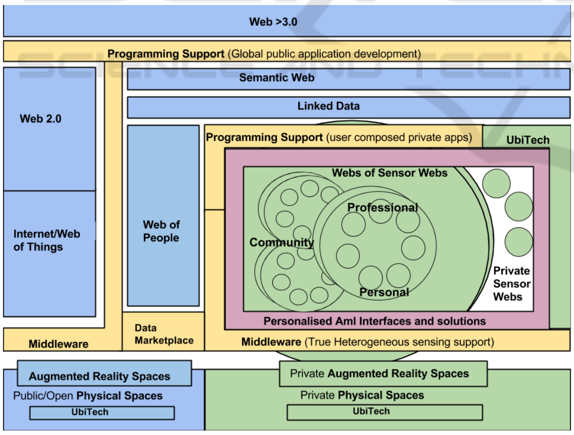

Figure 3: Middleware Enablement for Cyber-Physical-Social Web Greater Than 3.0.

Figure 3 further illustrates the proposed composition of ubiquitous and web technologies that will provide a foundation for future AmI solutions. Requirements for middleware and programming support are highlighted throughout as is a layer depicting user-centered, personalised, AmI solutions and interfaces. It is envisaged that private sensor webs with connecting users will form organically grown communities, or webs of sensor webs. Privately sensed information from a user's physical or web-based environments as well from publicly accessible data from Web 3.0 drive user-focussed services that adapt autonomously to user needs as they change over time. Private, community, regional and global sensor webs will underpin future smart spaces and environmental monitoring systems. It is anticipated that a data marketplace will facilitate users *selling* high level abstracted data to companies and service providers. The difference in this model is that the data resides with the user until they actively choose to share it. This will enable the provision of data providence visualisations that allow a user to understand how, where, when and why their information is being used, empowering them to make safer choices in terms of sharing private information.

Within the context of this unified cyber-physical-social web, middleware is required to bridge, seamlessly, existing and future infrastructures including WWW and Ubiquitous Computing deployments. Programming Support is required to unify access to the underlying infrastructures simplifying the development process for application domain experts.

5 CONCLUSIONS AND RESEARCH AGENDA

In this position paper, we considered AmI as a Cyber-Physical-Social paradigm. Having reflected on current state of the art in ubiquitous computing and web research, a future cyber-physical-social web was proposed as the contextual foundation that will underpin Cyber-Physical-Social AmI. The need for a generic middleware and software framework to enable this vision of AmI was articulated and Service Oriented Architecture identified as the appropriate solution for acheiving this aim. Based on this discussion, the following research priorities are identified:

- A deeper understanding of the need for cyber, in particular social, data within ambient intelligence solutions;
- A seamless and unified abstraction model of cyber (including social) and physical environments;
- Unified abstractions for middleware services supporting both WWW and ubiquitous computing initiatives
- An intuitive and feature rich middleware and programming framework for the rapid development of prototypes and testbeds.

This research agenda depends on collaborative efforts of researchers in the broad fields of WWW and Ubiquitous Computing research to deliver an infrastructure for user-centered cyber-physical-social AmI.

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