SenseCampus: Sensor enabled Cyber-Physical Coupling for Ubiquitous Services

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Abstract: Convergence between cyber and physical spaces is accelerating due to the penetration of various ubiquitous services based on sensors and actuators. Effective sensors such as ultra low-cost wireless sensors, smart phones and pads allow us to couple real objects, people, places, and environment with the corresponding entities in the cyber space. Similarly, soft sensors such as blog, facebook, twitter, foursquare and other applications create new types of sensed data for cyber-physical coupling. In this paper, we describe sensor enabled cyber-physical coupling for creating ubiquitous services in the SenseCampus project. We first classify cyber-physical coupling and ubiquitous services in the project. Several ubiquitous services, such as SensingCloud, DIY smart object services, Twitthings, Airy Notes, and Mebius Ring, are described. We then address the challenges in cyber-physical coupling for creating advanced ubiquitous services particularly for educational facilities.

Keywords: cyber physical systems, cyber physical coupling, sense campus, sensing cloud, HOT-SPA

1. Introduction

Ubiquitous services are becoming more popular as demonstrated by such smart devices as ultra low-cost wireless sensors, smart phones and pads in our everyday lives. In addition to the smart devices, applications on the web can be seen as *soft sensors*, including facebook, twitter, foursquare, etc., since they allow us to capture and gather new sensed data such as personal/group health, emotion or social context for social services. These services support our everyday activities as well as social activities.

Coupling objects, people, society, environment or phenomena in a real space with the corresponding entities in cyber space can create ubiquitous services. By coupling we mean that it allows both functions namely capturing something in the real space to the cyber space, and actuating something back to the real space from the cyber space. By just coupling entities in real and cyber spaces, a ubiquitous service can offer a various kind of awareness to the users of the service. For instance, a medical training service for mental disorders may offer a promising way of therapy by teaching patients to recognize and manage early warning signs by their own. Similarly, in personal mobile sensing applications, all members' mobile sensors are connected to the globally common web page. The service aggregates sensed data and visualize in the web page, improving the members' awareness of the community. In general, processing functions provide mining, analysis, or optimization functions.

To design ubiquitous services effectively, we model a ubiquitous computing system based on so called a "HOT-SPA" model. In this model, a system consists of sensing (S), processing (P)

and actuation (A) components. The "HOT" stands for "Here or There", and indicates the actual location of the component in a real space. We denote Sh, Ph, Ah, St, Pt, At for components located here or there respectively. Sensing components (Sh+St) provide sensing functions of real entities or phenomena in a real space and capture the sensed data into a cyber space. Processing components (Ph+Pt) interpret captured data and convert them to higher-level information, and decide a suitable action or a set of actions for the actuator. Actuation components (Ah+At) execute the requested action(s) as the outcome of the processing components. Then, the requested action(s) may change the status of real objects and it may initiate a new SPA cycle.

In the rest of the paper, we present sensor enabled cyber-physical coupling for creating ubiquitous services in the SenseCampus project. The project aims at making a university campus smart in the following three-fold. First, students as service *producer* are allowed to acquire and produce campus-specific real world information more efficiently. For example, they are enabled to join with their friends and faculties more smoothly with help of cyber-coupled people data. Second, faculty members can take advantages of cyber-coupled objects data to, for instance, know the empty seats in the cafeteria. Third, staffs can monitor the campus in finer-grained way with help of the cyber-coupled environment, students, and objects data. To this extent, we have been investigating the architecture of cyber-physical coupling that encourages various stakeholders to build their own HOT-SPA applications on it with privacy enhancement policies.

We first classify cyber-physical coupling and ubiquitous services in Section 2. We then show the architecture by describing novel ubiquitous services constituting the architecture, such as SensingCloud, DIY smart object services, Twitthings, Airy Note, and Mebius Ring sensors in Section 3. Section 4 addresses the

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challenges in cyber-physical coupling for creating advanced ubiquitous services, followed by the survey on related work in Section 5. Section 6 summarizes the paper.

2. Cyber-Physical Coupling

In this section, we classify cyber-physical coupling enablers, coupling entities and ubiquitous services.

2.1 Coupling Enablers and Entities

Coupling enablers provide both sensing and actuation functions for ubiquitous services. We classify these coupling enablers into two types: sensing enablers and actuation enablers. Sensing enablers are *hard* sensors such as ultra low-cost wireless sensors, RFID tags, light sensors, cameras, smart cards, smart phones, and *soft* sensors such as facebook, twitter, foursquare, flickr and other web applications. Actuation enablers are smart phones, pads, PCs, public displays, TVs, information appliances, traffic signals, mobile robots or embedded robots.

In particular, a smart phone has many sensing devices such as GPS, camera, accelerometers, illuminometers, microphone, cellular signal strength ratio, Bluetooth, WiFi, smart cards, and/or RFID tag readers. It has also many actuation devices like a display, a speaker set and a vibrator. Because of these functions, smart phones allow us to couple many entities in a physical space with objects in a cyber space. As shown in **Fig. 1**, we can depict the coupling relation between two entities, Ep and Ec with SPA components.

2.2 Ubiquitous Services

We define ubiquitous service as a service which can offer a set of functions or actions to support our everyday activities in a real space. While web services can be initiated in a cyber space, ubiquitous services are initiated in a real space based on a user's situation or context. They can be created by coupling objects, people, places, environment or phenomena in a physical space with a cyber space. Relationship among coupling entities between two spaces can be classified into the following relations: one to one, one to many, many to one, and many to many.

For instance, a remote nursing care system for an elderly person offers a ubiquitous service. It may consist of a sensor attached to the elder's mug cup (St), a caretaker's mobile phone (Ph), and a skype phone placed at the elderly person's home (At). Suppose that, one day, the care system detects no movement of the elderly person's mug cup during breakfast time, and then the system may send a warning message and initiate a phone call from the caretaker's smart phone to the elderly person's skype phone for checking out the person's condition.

Similarly, a runner's running support system also offers a ubiquitous service. A tiny sensor (Sh) attached to a running shoe or smart phone (Sh+Ph) can track the current location of the runner and share the runners' running records. A global enabler such as a runner's web page (At), like nike+'s challenge page^{*1}, makes us allow to link a personal data to a team data for participating the longest-running team ranking battle. In this way, a simple con-

Fig. 1 Cyber-physical coupling with a smart phone: one to one case.

Fig. 2 Classification of ubiquitous services.

nection between personal and global enablers makes us a richer ubiquitous service for supporting our activities.

2.3 Classification of Ubiquitous Services

The well-known feature of ubiquitous services is pervasive nature of the service functions or actions. We classify the ubiquitous services into two types: Any- or Only-cube type.

Any- or Only-cube Types

A ubiquitous service can be used at anytime, from anywhere and by anyone. We call this as an "Any3 (any-cube)" type service. Services are not designated for specific users in space and time. However, another type of services is often designated to a person or a specific group of people in space and time. We call this as an "Only3 (only-cube)" type service.

For instance, suppose a group of people who bought a product at a supermarket can get 50%-off of another product. If the supermarket's owner wants to offer further incentive to use e-cash, then the store can give more discount only to the users who used to pay the total amount by e-cash using their mobile phone. In this way, the store can reduce the congestion at the cashier area and customers who used e-cash could check out without additional waiting time. Another instance of Only3 services is public displays at the supermarket. They would show different advertisements depending on the time, the location of the display, and the gender and the age of the customer.

i-, a-, b-, c-, or d-zones

We can further classify ubiquitous services based on the region covered by the services as shown in **Fig. 2**. We divided the regions into 5 zones, namely i-, a-, b-, c- and d-zones. i-zone is around our body, and contains first-person services. a-zone is up to the area around the user (e.g., a room), and b-zone covers up to a building. c-zone covers up to an outdoor space where a user is connected to the Internet and GPS. d-zone is an outdoor space disconnected from the Internet and GPS connectivity. In

*1 <http://nikerunning.nike.com/>

an urban area, there are many tiny d-zone spots within c-zone and a ubiquitous service often faces difficulties with unexpected disconnection from infrastructure networks.

For instance, a location x of a car on a road in Fig. 2 can be mapped properly to the corresponding location x' in a car navigation system in a cyber space. Although the car navigation system with a smart phone can also provide a navigation service in c-zone, it may not be used in d-zone due to the lack of access to GPS connectivity. Similarly, when a user uses a personal indoor navigation system to find a location of a room in b-zone, the system needs to interact with an indoor location system such as active badge [1] or 3D bat [2].

3. SenseCampus

SenseCampus project aims at making a university campus smart achieving better information sharing among students, faculty members, and staffs. Coupling objects, people, and environment on campus supports their activities with more dynamic and real-time information. First, a student as service consumer is allowed to acquire campus-specific real world information more efficiently. For example, they are enabled to join with their friends and faculties more smoothly with help of cyber-coupled people data. Second, faculty members can take advantages of cyber-coupled objects data to, for instance, know the existence of particular books in the library. Third, staffs can monitor the campus in finer-grained way with help of the cyber-coupled environment, students, and objects data. In the following sections, we first describe the architectural technology to share sensed data globally, then show how the entities on campus are coupled.

3.1 SensingCloud

The architectural role of SensingCloud is to provide the infrastructural services to share sensor data within a certain region. Although our purpose is to couple entities on campus-wide, it scales up to worldwide sensor data sharing. The HOT-SPA model of SensingCloud is shown in Fig. 3. SensingCloud service enables applications to subscribe sensor data from arbitrary membership sensor nodes. It assumes there are stand-alone local platform, called *uBox*, for each sensor network domain. This gives an aspect of local resource management to each sensor network. Then we create a network of those local sensor network platforms with an add-on middleware, called *Global Gateway (GG)*, connecting *uBoxes* via the Internet with help of an Index Server as shown in Fig. 3. Users' smart phones are allowed to produce and consume sensor data via SensingCloud.

uBox is used to manage a single sensor network, which is initially built to make a certain environment smart. The administrators of the sensor network can register their sensors or actuators to this platform to export them to the users or developers within the network. They can register their internal administrative information to the platform since *uBox* is totally under their control and external user will not access the platform server directly. This helps simple private application development. *Global gateways* exchange geographical location of *uBox*, and form an overlay network on the Internet utilizing their physical distance as a metrics. Therefore, users can ask for the global sensor data to his local

Fig. 3 HOT-SPA model for SensingCloud.

gateway as well with global gateway. If user requests for temperature data around his location, it forwards the requests to its global gateway. Then global sensor network gateway passes the requests to global gateway that is within the target area or the closest one. The local platforms pass the request forward for N times and search the target sensors.

SensingCloud is based on a layered abstraction shown in Fig. 4. Each layer can be manipulated via a RESTful interface formatted as follows: `http://[server]/[local/global]/[sensor/actuator]/[layer]/[parameters]`. The target scope, namely local or global, can also be specified.

Entity: Direct Access To A Resource The bottom layer enables direct access to the resources with resource-specific identifiers. It supports registration, update, manipulation, and deletion of information of resources.

Class: Discovering Resources With this resource discovery layer, users can discover the sensors with specific type of data or actuators. For example, to collect temperature sensors tagged as “outside” and located within 1,000m radius circle from coordinates(49.00, 8.38), the user should make GET request to the url shown in Fig. 5 a).

Aspect: Processing Resources This layer processes multiple data and generates data that represent their aspect. For example users can create GET request such as shown in Fig. 5 b). They are also allowed to actuate towards the real world with the same facility. For example, `/local/actuator/aspect/light/poweroff?latitude=49.00&longitude=8.38&radius=100&tags=inside` would turn off all the lights within 100 meter radius on campus.

3.2 Coupling of Objects

The SenseCampus project also enables to sense how people interact with objects. Since there are many objects such as chairs, desks, computers or projectors shared among multiple users, sensing those objects enables us to know what is happening in the campus or to manage equipments efficiently. To manage such objects with sensor nodes, we have developed object coupling architecture constituting of the following functionalities.

Easy making ordinary objects to be sensible objects:

By attaching a tiny wireless sensor node to a user's belongings, the user can augment an object digitally in a cyber space and as-

Fig. 4 Layered abstraction of SensingCloud.

Fig. 5 Requests example for class, and aspect layer.

Fig. 6 Spot & Snap: Association between an object and a sensor node.

sociate the object with various services. For example, assuming that all the seats in the cafeteria are attached with a sensor node, we can know which seats are available, and then notify students waiting for seats. When using smart object services, a semantic association between a sensor node and a domestic object must be made before initiating any services. At a home environment, however, professional assistance with such instantiation may be either unavailable or too costly. To solve this problem, we proposed Spot & Snap interaction [3] that eases of such association with use of a USB camera with an LED spotlight (see Fig. 6). With Spot & Snap, non-expert users can register their belongings to preferred services without experts. Consequently, it provides application framework for programmers to create various smart object services [4].

Easy filtering objects' sensing data as context:

Since sensible objects can just send sensor data to network, filtering those data and detecting meaningful information is needed to leverage sensible objects to create various services. States of objects change every now and then. Users must define a part of this change in state as a context or a trigger of certain services, because users are domain experts of their own environment. However, since defining context is unfamiliar tasks for users, supporting users to define context by analysing sensor data from objects is required. To define the contexts easily without complex programming skills, we have developed objects' context description

language, called SOEML, based on temporal relation [5].

Easy sharing objects' context among allowed users:

Since many objects are shared in campus, their context also should be shared. We developed Twitter-based context sharing system, called Twitthings [6]. It is an extension of the smart object service by using social media, namely Twitter, as a group of remote actuators.

The advantage of Twitthings is that it enables users to share and define smart object event seamlessly and securely. Similar to the event and action association process used in SOEML, a user can define an event and tweet messages associated with Twitthings as shown in Fig. 7. If you follow the user in Twitter, you could see all incoming messages. These messages are automatically generated into the cyber space by the smart objects in the real world. The users can also define new events with the messages. For example, assume that a user receives messages regarding to a laboratory, "All chairs are used" and "Projector is used" from Twitthings. The user can define a new event "meeting" by associating it with those two messages. Once the event is registered to Twitthings platform, the events will be detected automatically, and users can use the events for various actions such as posting messages to Twitter or controlling appliances in the room. By using following and followers relationship in Twitter, users can form social network via their objects. Twitter also has a function to preserve privacy; it can prevent messages from revealing

Fig. 7 Concept of Twitthings (left) and user interface of Twitthings (right).

Fig. 8 Three Conversation Models: these depict the concepts of each model. S represents the speaker in the conversation, L is the listener, and P is the person acting both.

Fig. 9 Twitter message clustering results in the Tokyo metropolitan area.

to unapproved users.

3.3 Coupling of People and Society

One of the purposes in SenseCampus is to know various types of people's activities on campus. There are many researches to sense individual human behavior, such as identifying walking/running contexts. On the contrary, we focus to sense multiple humans behavior, since people often collaborate together on campus (e.g., students and faculties meet, discuss or study). If we can recognize people's behavior on campus, many applications, which enhance relationships among people, can be realized together with privacy enhancing technology.

One of the important people behaviors is *conversation group* context, which represents "where, when and with whom a user is making a conversation." Conversations on campus are classified into three models, "Broadcast", "Meeting" and "Chatting", according to the two criteria. First is how suddenly the conversation occurs. Conversations without a schedule agreed among conversation participants have high level of sudden occurrence. The second is the number of persons participating in the conversation. We show three conversation models in Fig. 8. People attending to a conversation are allowed to refer to the members in the group to, for example, exchange computer files necessary for

the collaboration.

Broadcast Model

It tends to have low level of sudden occurrence and usually has many participants. Examples of Broadcast's conversations include lectures in classes. These conversations often have fixed schedules of where and when to begin. Some research aim to analyze Group Conversation context using participants' location acquired from their mobile phones. This model has the characteristic that the groups have many participants, and locations of each user transit apparent. This, in turn, shows that conversation groups can be detected by acquiring user's location and population density, etc. On the contrary, we also focused relativity of chatting on social network. To group users who has same interests, we analyzed messages information on Twitter in terms of its location information [7]. Figure 9 shows classified message in Tokyo metropolitan area by K-means method. A color in the figure corresponds to a group of people who have the same interest. In the broadcast model on campus, we often confirm that people who attend the same class tend to send messages which have the same context and location. Therefore, classifying messages on social media has possibilities to detect the broadcast model in campus. We have been developing an application based on this technique to enhance mutual communication among students on

campus by forming groups of students with similar interests.

Meeting Model

It has a fixed schedule of time and place: Starting time and place are shared to conversation members beforehand. Some of the examples of Meeting models are, regular meetings of a laboratory, discussions with colleagues, or negotiation with suppliers. Meeting model involves fewer participants compared to Broadcast model, and participants interactively talk.

Meeting model can be detected using participant's schedule, because the schedule is usually shared amongst the participants. In addition, there are places where Meeting model usually takes place, such as meeting rooms or discussion rooms. Thus, this model can be detected from the user's schedule information or network sensed systems installed in the environments. We introduce a system that detects meeting context by monitoring the meeting room's objects in the next section.

Chatting Model

It has high level of sudden occurrence, and small number of participants. For example, there are stand talking in an office corridor, chatting with colleagues in a laboratory, conversations with friends who attended the lunch. It is difficult to predict time, location and members of the conversations in this model, because it occurs unexpectedly. Moreover, when using WSN to detect this context, it must be installed not only inside the buildings, but also outside of them. Hence, methods for detecting Broadcast or Meeting model cannot be used for Chatting model. However, Chatting context is effective when providing services to specific group of people, hence, the need for detecting Chatting context is high.

To acquire "conversation group," we extract chatting people (*conversation group*) from assemblages of people (*user set*). We created an algorithm which groups users by following three steps:

- (1) Step 1: Detect a user-set based on proximity between users
- (2) Step 2: Check if the user is talking to someone in the user-set
- (3) Step 3: Extract conversation groups from the user-set based on the result of phase 2

We confirmed that the algorithm achieves the grouping accuracy of 70 percent [8] by implementing it on Android Mobile Phones using Bluetooth RSSI to detect neighbouring users. Since most students have their own smart phones, we are planning to use this implementation on the Sensing Cloud infrastructure to enable active development of applications that leverage the chatting context.

3.4 Coupling of Environment

We also couple environment in the SenseCampus project to monitor the outdoor natural environment and the indoor. Airy Notes is our initial investigation of the outdoor environment monitoring, particularly microclimate monitoring, held in a park in Shinjuku, Tokyo. The Mebius Ring sensor network is on-campus environment coupling system based on the experiences from the Airy Notes project. As an indoor environment monitoring mechanism, we established a campus-wide energy consumption monitoring system. The detail of the system is described in the following sections.

Fig. 10 HOT-SPA model for Airy Notes.

Fig. 11 Access from a cell phone and map-based real-time monitor on the Web.

Airy Notes

In Airy Notes project [9], we monitored environmental condition using ultra low cost wireless sensor modules and showed the characteristics of places intuitively on a map in web (At) as well as on user's cell phone (Ah). Unlike a web-based monitoring system, we have attached a 2-D bar code with each sensor, so that a user can sense the data in front of the sensor using a cell phone's camera. The HOT-SPA model of Airy Notes is a hybrid model of a sensor gateway and P2P model as shown in Fig. 10.

The Airy Notes system is designed to help easy understanding of the effect of greening by enabling high density placing of sensor nodes. We conducted the experiments of the system in Shinjuku Gyoen with 160 sensors. The garden is known as taking part of keeping urban environmental condition calm with its green. We monitored the change of temperature, and observed that the temperature of the inner place was lower than the edge of the garden.

Airy Notes System enables on-site observation of current temperature and its temporal change on a cell phone of any user. As shown in Fig. 11 (left), users can casually see the characteristics of the environment by checking the QR code on the sensor at the point they are in. They would understand the environmental condition with their body sensation.

The data shown on the viewer are updated in real-time. Unlike existing environment monitoring systems that usually use a sensor module with a local storage unit, Airy Notes System utilizes wireless sensor nodes, and an on-line database system. Users can see the latest condition of the target region anytime. Figure 11 (right) is a map on which live temperature are shown as colors.

Mebius Ring and Energy Consumption Monitoring

Mebius Ring is an environment monitoring system on our campus that uses 16 wireless sensor nodes for monitoring temper-

Fig. 12 Mebius Ring sensor node location.

Fig. 13 Digits on the power distribution board.

ature, humidity, and light. **Figure 12** depicts the locations of Mebius Ring sensor nodes. Each sensor node of Mebius Sensor is product of Crossbow Inc. named eKo Mote^{*2}. This ZigBee-based sensor node has a solar battery panel, and is a part of a larger multi-hop network that covers a broad area. The Mebius Sensor system is designed to be a platform of various ubiquitous computing applications such as enhancing people's awareness of their natural environment.

Similarly to Airy Notes, users are allowed to monitor the sensed data in real-time via the viewer on the web, and via tweets on twitter^{*3}. In addition, we developed a Web APIs to enable applications to leverage sensor data of Mebius Sensor. Applications can fetch the data specifying a sensor node ID, date, and date type in URL.

Another monitoring system in the SenseCampus project is an energy visualization system that monitors energy consumption of our campus. It is a simple system that captures the four digits shown on the power control panel, shown in **Fig. 13(a)** using a small web camera. The captured data are stored in a remote database, and shown on the web^{*4} as shown in Fig. 13(b). We also provide a Web API for this system and a twitter service has been operated^{*5} using this API similar to Twitthings.

In total, we offer power consumption, temperature, humidity and brightness information. All the data we sense in the campus is open for all the students and give them an opportunity to easily build cyber-physical ubiquitous services. Students have already proposed some application ideas in a course work. One of them, for example, is an application that warns over-usage of energy to students combined with social network web applications. Also, some students are proposing a campus pedestrian navigation system that navigates you to the destination through the path with

lower temperature.

4. Related Work

Some projects on sensor network deployment share similar goals in that they aim at leveraging cyber-physical coupled data for context-aware actuation. Campus sensing [10], home sensing [11], structure monitoring [12], and environment monitoring [13] are their examples. Each deployed sensor network collects data into its associated sensor database. The collected data can then be used by applications that run locally in the network, or remotely via the Internet. This classic model is data-centric instead of user-centric in that it is optimized for efficient data collection into the centralized database, and users are always required to query in the database even when they are directly facing a sensor node. In the SenseCampus project, we enabled users to observe the environment directly and real-time using the users' cellular phone, and the web interface.

Global sharing of sensor data via the web has been investigated. IrisNet [14] provides a middleware system to share sensors among multiple computers within a city-scale. SenseWeb [15] aims at sharing sensor nodes worldwide. It proposes a software architecture for global sensor sharing assuming sensor, data, and application heterogeneity. GSN [16] also aims at the worldwide sensor sharing. While these research focus on the use of environment monitoring data on the web, we provide applications with data coupled with objects, people, environment and society. This enables applications context-aware services leveraging a range of the cyber-physical coupled real-world entities.

Several works have been done for object coupling, such as MediaCup [17], DigiClip [18], MAX [19] and Sentient Artifacts [20]. While they have proved the usefulness of cyber-coupled objects, their focuses are to use of objects that embeds computational capability. We have enabled end-users to make association between objects and sensor nodes to allow their own belongings instantly *coupled*. In addition, SenseCampus project

^{*2} <http://www.memsic.com/products/wireless-sensor-networks/environmental-systems.html>

^{*3} http://twitter.com/#!/mebius_sensor

^{*4} <http://www.sfc.keio.ac.jp/top.html>

^{*5} <http://twitter.com/#!/sfcpower>

aims at the *mashup* of data coupled to different types of entities in the real world: objects, people, environment, and society. Applications are allowed to acquire the data via the API in SenseCampus, and to serve richer context-awareness for end-users.

There are several classes of research towards effective use of user-side terminals for coupling of people and society. One common approach to this is called participatory sensing that makes use of cellular phones as a sensor [21]. Recent cellular phones contain a range of sensors including ubiquitous networked light, proximity, cameras, GPS, accelerometer, compass, and so forth. Due to their richer computational capability, phones can be used to capture context of users in the ubiquitous/pervasive computing perspective. Based on the captured context, they can provide user-aware digital services with them. Some urban sensing projects [22], [23], [24] utilize user-side terminals. Aquiba [23] is a system for achieving human probe capability in urban sensing. They leverage our Sense Phone for their purpose. MetroSense [24] defines a similar architecture that includes the notions of mobile sensors and static sensors. However, their goal is to share the data among users who participate in a sensing project. Their focus is thus closed in the interaction between the user-side terminals and sensors. In our project, we encourage stakeholders in our campus to create new applications by making the data open, establishing the set of APIs, and providing GUI on the web.

Environment monitoring using sensor networks have been practiced by several projects [13], [25], [26]. They include a sensor network to monitor severe places, such as volcano. Those projects install wireless sensor networks to couple environments into the cyber world, and collect data to a sensor database. We also conduct this data collection, however, as stated earlier, we also enable users and developers to leverage the data. This enables users to consume the data, and decide their behavior, such that a user decides to save energy looking at the energy usage on campus. Such behavioral change is captured into the cyber world, and again feed back to the user. This feedback loop is the major characteristic of our SenseCampus project.

5. Challenges in Enhancing Cyber-Physical Coupling

We have presented examples of ubiquitous services that were improved by using personal and/or global enablers such as smart phones, ultra low-cost wireless sensors, social media and P2P computing components. However, we are still facing many challenges for creating advanced ubiquitous services by enhancing cyber-physical coupling.

Scalability in HOT-SPA architecture

A global enabler allows us to connect Sh, Ph, Ah components with global St, Pt, At components easily. However, as we presented in Twitthings and SensingCloud, scalability and real-time issues are still remaining. For instance, a large event handling process is migrated into Twitter system, however, a user of Twitthings does not have any control over the response time. This may cause a problem in command and control applications.

Cross-domain Mashup

Mashup is a well-known method in web service development to create a new service by combining data or functions from mul-

iple existing services on demand. Among ubiquitous services, it is still difficult to create a mashup based on existing ubiquitous services based on various S-P-A components. In particular, service descriptions, service finding, and service binding protocols are different in service domains. Network robot services, for instance, have a potential to be personal or global enablers, however, we do not have common protocols nor a common directory to find a suitable robot for specific functionality as an actuator. Similarly, sensor-to-sensor or actuator-to-actuator protocols should be development to realize cross-domain mashup.

Interoperability among heterogeneous components

There are many useful sensors and actuators for creating advanced ubiquitous services. Among cooperating sensors and actuators, command and control protocols must be matched between a sender and a receiver. In order to improve the interoperability of heterogeneous sensors and actuators, we need to create a better protocol or protocol conversion mechanism as well as universal components description language. The improved interoperability would result a ubiquitous service created in a new application domain.

Security and Privacy Enhancing Technology

Social media, such as Facebook and Twitter, allows a ubiquitous service to utilize large amount of user profiles for creating highly personalized or context-aware services. However, for instance, real-time location information of a group of people has a potential to lead location-based discrimination in a small community. These privacy related information should be controlled by individuals to maintain time and space accountability. In particular, auditability and visibility of such data flows should be managed.

6. Summary

We presented sensor enabled cyber-physical coupling for creating ubiquitous services in the SenseCampus project. The cyber-physical coupling provides two functions namely sensing something from a real space and actuating something back to a real space. By coupling objects, people, places or phenomena in a physical space with a cyber space, ubiquitous services can be created easily. We demonstrated our cyber-physical coupling architecture by describing novel ubiquitous services constituting the architecture, such as SensingCloud, DIY smart object services, Twitthings, Mebius Ring sensors. We also addressed that the scalability, cross-domain Mashup, interoperability, security and privacy issues are key challenges in creating future advanced ubiquitous services.

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Reference

- [1] Want, R., Hopper, A., Falcão, V. and Gibbons, J.: The active badge location system, *ACM Trans. Inf. Syst.*, Vol.10, pp.91–102 (online), DOI: <http://doi.acm.org/10.1145/128756.128759> (1992).
- [2] Ward, A., Jones, A. and Hopper, A.: A New Location Technique for the Active Office, *IEEE Personal Communications*, Vol.4, pp.42–47 (1997).
- [3] Yonezawa, T., Sakakibara, H., Nakazawa, J., Takashio, K. and Tokuda, H.: Spot & Snap: A Bootstrap Interaction for DIY Smart Object Services, *The 8th International Conference on Ubiquitous Computing*

- (Ubicomp 2006) Video (2006).
- [4] Yonezawa, T., Sakakibara, H., Koizumi, K., Miyajima, S., Nakazawa, J., Takashio, K. and Tokuda, H.: uPackage – A Package to Enable Do-It-Yourself Style Ubiquitous Services with Daily Objects, *UCS*, pp.240–257 (2007).
 - [5] Yonezawa, T., Nakazawa, J., Kunito, G., Nakagata, T. and Tokuda, H.: SOEML: Smart Object Events Modeling Language based on Temporal Intervals, *International Journal of Multimedia and Ubiquitous Engineering*, No.3, pp.73–91 (2009).
 - [6] Yonezawa, T. and Tokuda, H.: Twitthings: Sharing, Discovering and Defining Things' Happening Using Wireless Sensor Networks, *International Conference of Internet of Things*, pp.21–23 (2010).
 - [7] Hiruta, S., Aida, H., Mori, M. and Tokuda, H.: GLOBES: A Spatio-Temporal Grouping Algorithm using Micro-Blog Entries, *IEICE Technical Report*, Vol.110, No.454, pp.279–286 (online), available from (<http://ci.nii.ac.jp/naid/40018762882/>) (accessed 2011-03-07).
 - [8] Karatsu, Y., Saijo, K., Nakazawa, J. and Tokuda, H.: User Grouping Method for Ad-hoc Conversations based on Proximity of Users and Speaking Volumes acquired from Portable Sensors, *International Conference on Networked Sensing Systems* (2011).
 - [9] Ito, M., Katagiri, Y., Ishikawa, M. and Tokuda, H.: Airy Notes: An Experiment of Microclimate Monitoring in Shinjuku Gyoen Garden, *Proc. IEEE 4th International Conference on Networked Sensing Systems (INSS 2007)*, pp.260–266 (2007).
 - [10] Rowe, A., Berges, M.E., Bhatia, G., Goldman, E., Rajkumar, R., Garrett, J.H., Moura, J.M.F. and Soibelman, L.: Sensor Andrew: Large-scale campus-wide sensing and actuation, *IBM Journal of Research and Development*, Vol.55, No.1&2, pp.6:1–6:14 (online), DOI: 10.1147/JRD.2010.2089662 (2011).
 - [11] Intille, S.S., Larson, K., Beaudin, J.S., Nawyn, J., Tapia, E.M. and Kaushik, P.: A living laboratory for the design and evaluation of ubiquitous computing technologies, *CHI '05 Extended Abstracts on Human Factors in Computing Systems*, pp.1941–1944, ACM, New York, NY, USA (online), DOI: <http://doi.acm.org/10.1145/1056808.1057062> (2005).
 - [12] Kurata, N., Spencer, B.F. and Ruiz-Sandoval, M.: Risk monitoring of buildings with wireless sensor networks, *Structural Control and Health Monitoring*, Vol.12, No.3-4, pp.315–327 (online), DOI: 10.1002/stc.73 (2005).
 - [13] Szewczyk, R., Osterweil, E., Polastre, J., Hamilton, M., Mainwaring, A. and Estrin, D.: Habitat monitoring with sensor networks, *Comm. ACM*, Vol.47, pp.34–40 (online), DOI: <http://doi.acm.org/10.1145/990680.990704> (2004).
 - [14] Gibbons, P.B., Karp, B., Ke, Y., Nath, S. and Seshan, S.: IrisNet: An Architecture for a Worldwide Sensor Web, *IEEE Pervasive Computing*, Vol.2, No.4, pp.22–33 (online), DOI: <http://doi.ieeecomputersociety.org/10.1109/MPRV.2003.1251166> (2003).
 - [15] Grosky, W.I., Kansal, A., Nath, S., Liu, J. and Zhao, F.: SenseWeb: An Infrastructure for Shared Sensing, *IEEE Multimedia*, Vol.14, No.4, pp.8–13 (online), DOI: <http://dx.doi.org/10.1109/MMUL.2007.82> (2007).
 - [16] Aberer, K., Hauswirth, M. and Salehi, A.: Infrastructure for Data Processing in Large-Scale Interconnected Sensor Networks, *Proc. 2007 International Conference on Mobile Data Management*, pp.198–205, IEEE Computer Society, Washington, DC, USA (online), DOI: 10.1109/MDM.2007.36 (2007).
 - [17] Beigl, M., Gellersen, H.-W. and Schmidt, A.: Mediacups: Experience with design and use of computer-augmented everyday artefacts, *Computer Networks*, Vol.35, No.4, pp.401–409 (online), DOI: 10.1016/S1389-1286(00)00180-8 (2001).
 - [18] Decker, C., Beigl, M., Eames, A. and Kubach, U.: DigiClip: Activating physical documents, *Proc. 24th International Conference on Distributed Computing Systems Workshops*, pp.388–393 (online), DOI: 10.1109/ICDCSW.2004.1284059 (2004).
 - [19] Yap, K.-K., Srinivasan, V. and Motani, M.: MAX: Human-centric search of the physical world, *Proc. 3rd International Conference on Embedded Networked Sensor Systems (SenSys '05)*, pp.166–179, ACM, New York, NY, USA (online), DOI: <http://doi.acm.org/10.1145/1098918.1098937> (2005).
 - [20] Fujinami, K. and Nakajima, T.: Sentient Artefacts: Acquiring User's Context Through Daily Objects, *Embedded and Ubiquitous Computing – EUC 2005 Workshops*, Enokido, T., Yan, L., Xiao, B., Kim, D., Dai, Y. and Yang, L. (Eds.), Lecture Notes in Computer Science, Vol.3823, pp.335–344 (2005).
 - [21] Lane, N., Miluzzo, E., Lu, H., Peebles, D., Choudhury, T. and Campbell, A.: A survey of mobile phone sensing, *Communications Magazine, IEEE*, Vol.48, No.9, pp.140–150 (online), DOI: 10.1109/MCOM.2010.5560598 (2010).
 - [22] Hull, B., Bychkovsky, V., Zhang, Y., Chen, K., Goraczko, M., Miu, A.K., Shih, E., Balakrishnan, H. and Madden, S.: CarTel: A Distributed Mobile Sensor Computing System, *4th ACM SenSys*, Boulder, CO (2006).
 - [23] Thepvilojanapong, N., Konomi, S. and Tobe, Y.: A Study of Cooperative Human Probes in Urban Sensing Environments, *IEICE Trans.*, Vol.93-B, No.11, pp.2868–2878 (2010).
 - [24] Campbell, A.T., Eisenman, S.B., Lane, N.D., Miluzzo, E. and Peterson, R.A.: People-centric urban sensing, *Proc. 2nd Annual International Workshop on Wireless Internet (WICON '06)*, ACM, New York, NY, USA (online), DOI: <http://doi.acm.org/10.1145/1234161.1234179> (2006).
 - [25] Martinez, K., Hart, J. and Ong, R.: Environmental sensor networks, *Computer*, Vol.37, No.8, pp.50–56 (online), DOI: 10.1109/MC.2004.91 (2004).
 - [26] Werner-Allen, G., Lorincz, K., Johnson, J., Lees, J. and Welsh, M.: Fidelity and yield in a volcano monitoring sensor network, *Proc. 7th Symposium on Operating Systems Design and Implementation (OSDI '06)*, pp.381–396, USENIX Association, Berkeley, CA, USA (online), available from (<http://portal.acm.org/citation.cfm?id=1298455.1298491>) (2006).

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