Approaching Intelligent Environment through Sentient Artefacts

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***Abstract*— Sentient artefacts are everyday objects augmented with value added digital services. Being the building blocks of our surroundings, these artefacts can incrementally integrate computing into environment and can convert it into an intelligent one economically. In this paper, we report our experiences with sentient artefacts to rationalise intelligent environment. We discuss the design principles of sentient artefacts and present a sensor selection framework to convert a regular artefact into a sentient one. In addition, we discuss the application development guideline and lessons that we have learnt through prototyping sentient artefacts and proactive applications.**

***Keywords*—Sentient Artefact, Intelligent Environment, Ubiquitous Computing.**

I. INTRODUCTION

Tagging everyday objects with sensors and actuators to build instrumented environment is a common practice in ambient intelligence domain. Several prototypes and applications are demonstrated in the laboratory environment over the years [3,10,11,15,16,21,22,23,24]. However there is very minimal interoperability among the design principles of these projects and the underlying infrastructures can rarely be shared among isolated applications. The primary reason behind this phenomenon is the missing rationale of design and integration of smart artefacts in large-scale legacy applications. Another impediment that limits ambient environments proliferation beyond laboratory set-up is the installation cost. Enabling technologies e.g. location-sensing system, vision based recognition systems etc. requires complex infrastructures to be embedded in our environment, which increases deployment cost thus fails to attract mass population.

In this paper, we address these issues by sharing our experiences of intelligent environment formation using *sentient artefacts,* an approach that attempts to provide a practical, reusable and economical solution to rationalise intelligent environment. Sentient artefacts are everyday objects augmented with various kinds of sensors and actuators that suit their appearance and primary functionalities. This augmentation allows these artefacts to provide value added functionalities (so-called context like: state-of-use, environment attributes etc.) beyond their primary roles. For example, consider a frying pan, its primary use is in the kitchen. However we can utilise the frying pan by augmenting it with some sensors to infer that its owner is in the kitchen or cooking while the frying pan is being used. These artefacts are independent of any underlying sensing infrastructure but can create a federation among themselves leading to the formation of a self-aware intelligent environment in a bottom up manner. Since these artefacts are already available in our surroundings, we can rapidly convert our surroundings into a smart one.

We have been prototyping various types of sentient artefacts and applications integrating them. Over the years we have experienced several interesting issues regarding these artefacts' design, sensor selection, application development steps etc. In this paper, we have reported our experiences on these issues that we believe will contribute to align on some key aspects of design and integration of smart objects to rationalise ambient environments.

The rest of the paper is structured as follows. In section 2 we describe the design principle of sentient artefacts illustrating some of our prototypes. Section 3 presents a sensor selection and fabrication framework that we have designed to convert regular artefacts into sentient artefacts. In section 4 we discuss the augmented artefact based application development guideline whereas in section 5 we discuss the lessons we learned looking at some generic issues. Section 6 briefly presents the related works and finally section 7 concludes the paper.

II. DSESIGN PRINCIPLES AND ILLUSTRATIONS

In this section, first the design principles of sentient artefacts are mentioned followed by the illustration of some of our sentient artefacts.

A. Design Principles

Sentient artefact is a mere everyday object without any noticeable features. We augment sensors or actuators to make it self-aware. By doing so we extend its functional advantages as it can provide value added services beyond its primary role. The primary design principles that we have followed while building sentient artefacts are as follows.

1) *Complying with Primary Role:* This first design principle ensures that the additional functionalities of an artefact do not conflict with its primary role. For example: a mirror can be augmented to display some

personalized information complying with its primary role of reflecting images but we must not augment a mirror with a vibrator to notify some events.

2) *Natural and Implicit Interaction:* The augmentation should not introduce any new interaction technique. The interaction should be implicit and natural. Humans develop a mental model regarding the usage of everyday artefacts and sentient artefact should comply with that mental model. For example, if we augment a chair with additional services the basic interaction of users with that chair should remain same as before, e.g. sitting, putting staff on it etc.
3) *No Dedicated Sensor Infrastructure:* Next design principle ensures that each artefact is developed independently following some guidelines. They can work in a cooperative manner to form a federation but must not rely on a centralized sensor infrastructure for activating the value added functional services.
4) *Reusability:* The artefacts should be reusable. We must not augment an artefact for a specific application scenario. Rather the generic affordability of an artefact should be analyzed beforehand to ensure its reusability.

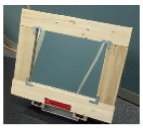
Following these primary principles, we have built several prototypes of sentient artefacts. In the next subsection, some of those prototypes are illustrated.

B. *Illustrations*

Sentient Table [7]: Projector augmented table that acts as an ambient display. Also RFID Base Station is embedded for user identifications.

Sentient Chair [17]: Provides state of use information utilizing embedded sensors. Such state of use and direction of the chair can be used to infer users activity hierarchically.

Sentient Tray [7]: Augmented with RFID Base Station and pressure sensors. The tray can specify the objects that are on top of it. Objects are tagged with RFID.



AwareMirror [18]: Embedded with infrared sensor and acrylic board, the mirror acts as an ambient display while sensing the human presence in front of the mirror.

Sentient Toothbrush [18]: An ordinary toothbrush augmented with RFID and accelerometer. It can be used as an identifier and can notify brushing events.

For detail of these artefacts and other sentient artefacts please refer [7,17]. These augmented features of the ordinary artefacts allow us to acquire real world context information or to provide some additional services.

III. SENSEOR SELECTION FRAMEWORK

The design principles mentioned in the previous section provides a very abstract guideline to build sentient artefacts. However, we have found that converting a regular artefact into a sentient one by embedding sensors and actuator is highly influenced by developers' intuition. Because of this, it is hard to justify the ad-hoc selection of sensors or actuators. Such ad-hoc way also limits a developer to repeat the steps to build artefacts rapidly and consistently. In this section, we describe a framework to select suitable sensors and actuators for respective sentient artefacts in a systematic way. Our framework is based on our earlier work proposed in [17]. We have modified the earlier model from generic point of view while looking at the functions rather than "state-of-use" as the premier. The key point utilized for appropriate selection is the relationship between a user and an artefact. The discussions in existing work show the catalogues of sensors that are utilized to specify a sensor from the target phenomena's point of view [2,20]. However, it lacks analysis of earlier stages in terms of selecting appropriate sensors for artefact augmentation, i.e. what kind of state can be extracted, what kind of interaction is remarkable for the context extraction, what kind of phenomenon can be observed from the interaction, what quality attributes are significant etc. Our framework provides a sentient artefact developer with a systematic way to handle these questions. Namely, it provides a way to answer a question like *"What kind of phenomenon is remarkable to augment additional functionality to the target artefact most accurately?"* The framework consists of five steps:

Step 1 ~ Specify the Required Functionality: This step is to answer the basic question like "What functionalities are required from the artefact?" This question can further be decomposed into two detail parts: level of abstraction and type of functionalities. As depicted in Fig. 1 an office chair can offer two types of usage: the regular usage as a chair and putting an object on it. In the former case the chair can provide presence of a person, his activity (sitting), and way of sitting (leaning back) etc. In the later case the chair can provide objects' presence, weight etc. So for a chair, these can be the additional functionalities and the abstraction is the state-of-use Therefore, first of all a developer has to clarify his/her requirements for the augmentation. They should assess carefully whether the target artefact provides required functionalities considering its affordability.

Step 2 ~ Analyze the Artefact's Usage and Interaction: The next step is to analyze the specified usage to answer the question "How to use it? How to interact with it?" The result of the analysis classifies the usage into primitives, which include putting, removing, touching, leaving, pushing, pulling, rotating, shaking, approaching, leaving, storing, etc. For example, in the case of sitting on a stool depicted in Fig. 1-left, a user's hip is "put" on the seat with some force, while a person sitting on an office chair (Fig. 1-centre/right) can `"rotate" it and lean on the back seat, i.e. "touching". Moreover, it is important to identify the frequency of movement that may affect sensor's responsibility. In the case of the above office chair, the relationship between a person and the back seat can be changed frequently since he/she might bend and lean, while the relationship between a person and the seat do hardly change. Therefore, to extract the presence of a person, one or more sensors should be attached primarily on the seat, and those of the back seat should be provided to supplement the primary ones. This analysis allows a developer to augment the appropriate functionality to the artefact and to find the appropriate sensor/actuator fabrication position considering its primary interaction techniques and usage.

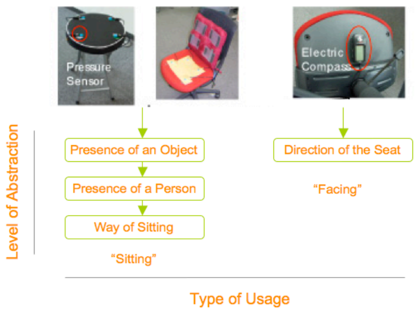


Figure 1: Heterogeneity in Artefact Usage and the level of Abstraction

Step 3 ~ Clarify Observable Phenomena: The third step is to clarify the observable phenomena against the primitives. For example, when something is "put" on the surface, there might be physical phenomena like the change of pressure on the surface, the vibration of the surface, noise, the change of temperature on the surface, the change of electric capacitance, etc. Although almost the same phenomena can be observed in the case of "touching" on the back seat of a chair, it is difficult to detect the change of temperature because the "touching" happens so often while the speed of changing temperature is slow. This means that "leaving" from the back seat might happen before a temperature reaches at a dedicated level. By the end of this step, the phenomena that contribute to augment the specified functionality become clear.

Step 4 ~ List the Candidates of Sensors: Several works in the literature investigates how to sense a specific phenomenon, e.g. [2,20]. Namely, the answer to the question like "What sensor can measure a change of force?" is easily found. There may be more than one sensing technology for each phenomenon, which will be identified in the final step.

Step 5 ~ Select the Appropriate Sets of Sensor: This is the final stage of the framework, where the most preferable sets of sensors are identified from many aspects, e.g. qualities, performance, form factor, cost, power consumption, availability, aesthetics, etc. The trade-offs needs to be resolved based on overall requirements for the prototyping or product.

A. Illustration of the Framework Usage

Figure 2 illustrates a part of the framework utilization, that represents the selection flow for a person's presence on an office chair, i.e. sitting on a chair. In step 1, it begins with the functionality of interest, i.e. "presence notification", which can be decomposed into two relationship: 1) "putting" his/her hip on the seat and 2) "touching" his/her back to the back seat in step 2. Then, in step 3, five types of phenomena are identified, and then in step 4, seven types of sensors are extracted based on the phenomena. Finally, in step 5, a photo sensor and force sensor are selected for "hip-on-the-seat" detection, while a force sensor and touch sensor are chosen for `"back-touching detection". To enhance the reliability, multiple sensors of same types are used. Temperature sensor, mechanical switch, microphone, and IR (infra-red)/US (ultrasonic) sensors are rejected due to fragility, low response speed, and/or privacy violation.

Our proposal is not concrete structure of a selection flow; instead these five steps systemize the appropriate selection and fabrication of sensors and actuators based on artefacts affordability that we learnt from our experiences. The selection flow should be improved by the evaluation after prototyping, and also it should be extended incrementally through the development. Sharing the selection flow with others allows an artefact developer to repeat the steps of a successful development resulting in making the sentient artefact development process rapid, consistent, efficient and free from ad-hoc design. Sentient artefacts typically participate in the intelligent environment as components of proactive applications. In most of the cases, several artefacts act in a collaborative manner to build the intelligent environment hosting the proactive applications. In the next section we will describe the application development guideline with sentient artefacts for proactive applications in intelligent environment.

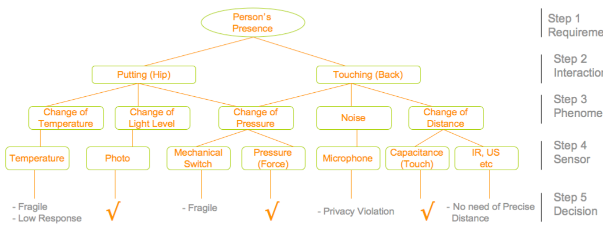


Figure 2: An Example of Framework Usage (For Person's Presence of an Office Chair)

IV. APPLICATION DEVELOPMENT GUIDELINE

In the previous two sections we have discussed the design principles and development process of sentient artefacts. These artefacts play the role of primary components in proactive applications. In this section, we will focus on the representation of these artefacts and the application development phases involving them.

A. Artefact Representation

Typically, some system infrastructures (middlewares) enable augmented physical artefacts to have digital representation henceforth being used in proactive applications. We have build two different middlewares Bazaar and Prottoy [6, 19] for this purpose namely to represent physical artefacts digitally from two perspectives. In Bazaar our primary goal was to collaborate spatially distributed artefacts in a centralized repository as a host of artefacts augmented functionalities where as in Prottoy we have focused on encapsulating each artefact as a self dependent one that can co-operate with other peer artefacts and provides applications to access its services directly. For detail of these middlewares please check the references. However, here we are reporting two major issues that we have learned through the development of these middlewares and using them for representing sentient artefacts.

1) *Artefact Abstraction:* Typically in intelligent environment middlewares like [1,16,23,25] context is represented as an independent entity even though a single artefact can provide multiple contexts. They employ kind of aggregator that merges the contexts. We followed the same paradigm in Bazaar. However, the problem of this approach is in handling cases where an artefact provides multiple contexts or if an artefact provides both context and service. If contexts collected from single artefacts need to be computed again or if accessing same artefacts' context and service requires different methods, it increases the development task and complexity. A solution to this issue is using the artefact itself as the abstraction of its functionality that may include multiple contexts and services. The implication of this approach is explained in the next point more clearly.

2) *Profile Based Artefact Representation:* Sentient artefacts can provide various functionalities. It is not logical to consider that each artefact should have only one functional role. For instance, consider a mirror, we can use the mirror as an ambient display. Simultaneously, the mirror can provide position information (whether some one is in front of it or not) if we embed proximity sensors into it. Similarly a stand light can provide lighting service or the ambient light level of the environment. The software component that is representing the light or the mirror must handle these multiple functionalities within the same artefact space. That means it must not be tightly coupled with the underlying functionality, like for each function or context, one soft component. Instead it should provide loose coupling among artefacts functional features while at the same time de-coupling the functional spaces for each function within the artefact. For instance, one application may use the display service of the mirror where another application may have interest in the position information that it provides. In such case we must not implement two software components, instead one artefact with two functional features. Similarly two different applications may be interested on a single function that several artefacts implement. In such case the application can select any artefact that is suitable for the scenario. Considering these, our solution is to use a profile based approach for artefacts [8]; an artefact can provide multiple functionalities and each functionality is encapsulated into one profile. All the profiles are finally integrated into single software instance that represents the physical artefact in the digital space.

B. Application Development Steps

In the previous sections we have mentioned about the artefact design, development and representation in digital space. Once these steps are done, the final step is to build proactive application integrating them. Based on our application development experiences we have systemized the development phase in few steps. In the following these steps are mentioned.

1) Draw the scenario for the proactive application/s.
2) Identify the functionalities of the application/s for implementing the scenario.
3) Identify the context information and service requirement for the scenario functionalities.
4) Identify what artefacts can be used for providing the required context information and/or service.
5) Consider all possible artefacts availability Develop the artefact by following sensor selection framework.
6) Integrate the artefacts into one or more applications to implement the scenario using a suitable middleware that provides artefact abstraction and profile notion.

V. Discussion

In the previous sections we have shown how sentient artefacts and proactive applications can incrementally form an intelligent environment. In this perspective we have learned several lessons on some generic issues from our experience. In this section we will discuss those issues and will put forth some open issues that are in our future work plan.

A. Sentient Artefact based Location System

An interesting passive advantage of sentient artefacts is their roles in location sensing. Some of the artefacts in our environment are static in nature and we rarely move them; like a refrigerator, a bed etc. Furthermore, these artefacts usually have a designated location, like refrigerator in the kitchen, bed in the bedroom etc. So, we can augment these artefacts with the capability of sensing location of their peer mobile artefacts (like a chair, a coffee mug, a knife etc.) and the pre-designated location of the static artefact can be used as the location of the mobile artefacts. Since, most of the time the precision requirement of location information is in the degree of few meters for proactive applications in intelligent environment, such sentient artefact based location sensing may pose an inexpensive and lightweight solution while eliminating the need of any dedicated sensing infrastructure. We have built a prototype system utilizing this feature of sentient artefacts incorporating their ecological relationship [9].

B. Natural Intercation

Sentient artefacts are mere regular artefacts that we are used to with in our everyday life. Thus improvising these artefacts might conflict users' mental model unless the interaction and functionalities of the artefacts are familiar and natural to the users. A display-augmented mirror must be a mirror in first case; the display functionality is just its value addition. The relationship between an artefacts' physical nature and digital functionalities must be natural that activate the cognitive and cybernetic dynamics that people commonly experience in real life, thus persuading them that they are not dealing with abstract, digital objects but with physical real objects. This results in reduction of the cognitive load, thus increasing the amount of attention on content. So maintaining such natural interaction while augmenting an artefact is a critical success factor for sentient artefact based approach.

C. *Privacy Concerns*

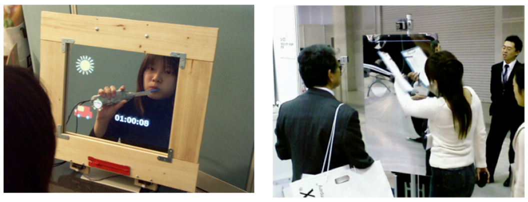
In all of our prototypes we have augmented artefacts with low-level sensing technologies, e.g. accelerometer, infrared range finder, etc. This is because of these sensors are less vulnerable to privacy violation. A video camera and microphone can be utilised to detect rich context like user's activity, identity, location, and even emotion and intention without explicit input. However, our user survey at the AwareMirror [18] project has revealed the obtrusive feelings of “being watched” of the subjects even though they know the benefits of the method. We consider users know the trade-off between the relevance of information and the efforts they need to keep it secret. Therefore a system should separate the contents utilisation, (e.g. using the identity) from the acquisition method (e.g. sentient artefact-based, biometric-based, etc.).

D. *User Centric Personalization*

When we talk about intelligent environment, often the term personalization is misinterpreted. This is because of the presumption of the self-aware characteristics of proactive applications. However, if the self-aware characteristics conflict with users’ preference, the applications’ success ratios drop radically. Every user has his/her own understanding and perspective towards an application and wants to personalize it regardless of its proactive behaviour. For the success of the application, we have found in our sentient artefact based applications that it is mandatory to provide personalization features in proactive applications. Here by personalization, we mean the active involvement of the end users to customize the adaptive behaviour of the system and participation of specific artefacts into the collaborative intelligent environment. For example, in the evaluation of intelligent workspace application we have found that most of the users do not want the system to play music and to turn on the lamp automatically rather like to have options for providing their preferences. So providing user-centric personalization control is very important in sentient artefact based applications and in general proactive applications.

E. *Usability and Aesthetic Appeal*

Sometimes an aesthetic artefact becomes difficult to use and vice versa. We strongly believe that we need a balance between usability and aesthetic appeal. Our hypothesis was that sentient artefacts would attract more people to use context aware services in their daily life since they promises to be more socially evocative. One of our major concern was to follow Norman’s guideline [4,5] to match the emotional appeal of such everyday artefacts. From the experience, interaction and user evaluation we have found the results that validate our hypothesis. Fig. 3 shows the two versions of AwareMirror [18] where the second version that is aesthetically more appealing (Fig. 3-b) attracted more people even though the functionalities were same in both the versions. So, the appearance solely was the critical factor. In fact aesthetic and emotional appeal play an important role for the success of such augmented artefacts. The computation functions are just the value addition. The important challenge is to identify how to integrate the value added services into everyday artefacts in a way that the physical appearances and functional features become inseparable from the aesthetic appeal of the interface thus making the artefacts a successful one and welcomed by all.



(a) (b)

Figure 3: Two versions of AwareMirror

F. *Future Work*

From our experience and user studies we have seen that, when augmented artefact notion is introduced, peoples expectation crosses the limits of current technology’s capability. Well, if so then what approach we should take to satisfy the end users while keeping our basic goal intact with the available technology? There are very few natural objects in our everyday life. Most of the objects that are integral part of our life are artificial. If we leap ahead, and consider that, our current approach incrementally augment all these artefacts, then what will happen? What system support do we need to support the co-operation? In fact what vision is necessary to utilize the array of augmented artefacts? We are currently working on these open issues and hope to come up with some concrete findings in near future.

VI. Related Work

Most of the projects in ambient intelligence domain use artefacts that are either traditional general purpose computing platforms ranging from small handheld to large sized high end computers or dedicated sensing infrastructure designed for providing specific contextual information. However our work is different from these two approaches as we concretely focus on everyday objects for context capturing without compromising their primary role. From deployment perspective, Sentient Computing [22] proposed a location sensing system that utilises the ultrasonic and radio frequency signal [26]. To measure the position of an object within a cubic inch, it requires dense ultrasonic transceivers, which is impossible to deploy and maintain without special cares. Moreover, the system provides only location context, which means a system's awareness of a user's context is limited. However, a sentient artefact provides its user's state-of-use as a primary context of the user, so the information source is closer to the user, which is considered to be more accurate and meaningful to him/her. Furthermore, it can play various kinds of functional role. Increasing different types of artefacts increases the context and services. Therefore, neither precise nor dense location sensing system is required. Other intelligent spaces in the literature focuses primarily on designated locations like meeting room etc. while exploiting a centralised dedicated infrastructure and /or dedicated terminals/artefacts for specific role playing [3,16,23]. However, sentient artefact provides a flexible approach to achieve the similar functions while omitting the centralised and dedicated constraints. Furthermore, sentient artefacts are the existing regular artefacts; their augmentation only increases their functional roles. As a result, sentient artefacts provides economical and reusable solution to approach intelligent environment,

From artefact augmentation point of view: Digital Décor [14] project augments traditional drawer and coffee pots to use as a smart storage and a media for informal communication respectively. However users are responsible for explicitly using these artefacts for their services. Also they only provide some services (searching, communicating with people etc.) rather than any contextual information. Tangible Bits [10] project attempts to bridge the physical world and virtual world by providing interactive surface, graspable objects and ambient media. However such explicit dedicated interfaces violates our design principle of natural interaction and natural augmentation of conventional everyday objects. Our focus is more general and by using multiple sensors embedded in the sentient artefacts we approach a more reliable and unobtrusive functionalities. MediaCup [21] projects and its succeeding SmartIts [13] provide insight into the augmentation of artefacts with sensing and processing. Our work is greatly influenced by them and exploits the Aware Artefact model introduced in [12]. However our sentient artefacts do not require any explicit interaction as MediaCup or SmartIts based artefact requires. Our approach is to make artefact aware but not their user aware of this fact. Sentient artefacts are mere everyday artefacts without any noticeable feature. Users manipulate them in the natural way they are used to with. They don't need to do something explicitly to make something happen. This natural feature distinguishes our work from other

VII. CONCLUSION

Smart object research has matured over the years. However, unfortunately there is little or no successful deployment of large-scale legacy application albeit numerous prototypes have been developed in the research laboratories. The primary reason is the missing rationale among the projects with similar goals resulting in the re-invention of wheels over and over. It is the time to focus on current practices and align on some key issues to continue the rapid progress of smart objects to realistically build intelligent environment. In this paper, we have provided our experience report of last few years in a concise way. Design principles of sentient artefacts, sensor selection and fabrication methods and application development guidelines are mentioned illustrating their implications. We believe our approach provides a feasible, practical and economical solution to rationalise intelligent environment and will help the community to gain some insights of sentient artefact based intelligent environment formation and rapid prototyping of proactive applications.

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