A Design Theory for Pervasive Information Systems

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Abstract. Pervasive Information Systems (PIS) constitute an emerging class of Information Systems where Information Technology is gradually embedded in the physical environment, capable of accommodating user needs and wants when desired. PIS differ from Desktop Information Systems (DIS) in that they encompass a complex, dynamic environment composed of multiple artefacts instead of Personal Computers only, capable of perceiving contextual information instead of simple user input, and supporting mobility instead of stationary services. This paper aims at proposing a design theory for PIS. In particular, we have employed [46]'s framework of Information Systems Design Theories (ISDT) to develop a set of prescriptions that guide the design of PIS instances. The design theory addresses both the design product and the design process by specifying four meta-requirements, nine meta-design considerations, and five design method considerations. The paper emphasises mainly on the design theory itself and does not address issues concerning its validation. However, in the concluding remarks we briefly discuss the activities we undertook to validate our theoretical suggestions.

1 Introduction

Information technology (IT) artefacts are already embedded in more places than just our desktop computers, providing innovative services in ways unimaginable in the near past. This shift in the viewpoint of information systems (IS) is commonly referred to as 'post-desktop' [21] or 'ubiquitous' computing [48]. This trend has fired a shift away from computers towards computerised artefacts. A new generation of information appliances has emerged [38], differing from traditional general-purpose computers in what they do and in the much smaller learning overhead they impose on the user. Instead of having IT in the foreground, triggered, manipulated, and used by humans, nowadays we witness that IT (irrespectively whether it comprises of computers, small sensors, or other communication means) gradually resides in the background, monitoring the activities of humans, processing and communicating this information to other sources and intervening should it be required. This new class of IS is often called 'Pervasive Information Systems' (PIS) [9] and enables new interaction means beyond the traditional desktop paradigm.

Specifically, DIS through their form of personal computers or other stationary access devices, were designed to fit into an office environment and the activities

taking place there. They were designed to be efficient tools in the hands of professionals. Thus, their practice of interaction design is directed towards this setting. Moreover, these systems are designed *for use*; this means that their design and evaluation are accomplished on the basis of some definition of their functionality and perceived usage. Thus, designers seek a solution that satisfies the basic criteria for usability such as efficiency in use, low error rate, and support for recovery from error, based on a general knowledge about what to do and what not to do to meet such criteria [16, 32]. The objective is to achieve *maximum usability* with respect to a general, precise notion of use, and the design is motivated by this ambition.

Consequently, the existing design approaches for DIS follow the same rationale. Design methods such as SSADM [47], ETHICS [31], SSM [10], or Object-Oriented Analysis [29] to name but a few popular methods, consider systems that support predefined tasks and in many cases assume a job or office environment. Moreover, such methods rely on the knowledge of the designer in order to recognise potential problems and mostly offer a generic approach to design. Also, such methods tend to focus on details of systems, something which is possible with traditional, static systems, but which cannot always happen for the dynamic and rich environments supported by pervasive systems. Finally, all the traditional approaches are oriented towards the fundamental tenets of Human-Computer Interaction: design for a specific user, performing a specific task, in a specific domain [36].

This position paper aims at proposing a methodological approach that may facilitate designers to develop PIS instances. Specifically, we will present a design theory for PIS. The following section presents the design challenge of PIS. Section 3 briefly introduces the methodological framework that will be used to specify the design theory, while section 4 presents the theory itself. The final section concludes with a critical appraisal of the proposed design theory and its practical usefulness.

2 Information Systems Design Theories

To specify our design theory we have followed the framework of Information Systems Design Theories (ISDT) that was first articulated by [46]. An ISDT aims at the design of classes of Information Systems, rather than the development of specific IS instances. To this end, design theories are prescriptive, in the sense that they provide constructs and guidelines for the achievement of stated goals, rather than explaining phenomena (explanatory theories) or predicting outcomes (predictive theories). Finally, design theories are theories of procedural rationality [42], as their objective is to prescribe both the properties that an artefact should have if it is to achieve certain goals, and the methods of artefact construction.

According to [46], design theories have two aspects; one dealing with the product of design (the artefact that will form the outcome of applying the design theory) and another dealing with the process of design (i.e. the method by which the design product can be realised). We will use this distinction to describe the components that form an ISDT. These components are summarised in the following table.

Table 1. ISDT Components.

DESIGN PRODUCT	
Kernel Theories	Theories from reference disciplines that govern design requirements
Meta-Requirements	The class of goals to which the theory applies
Meta-Design	A class of artefacts hypothesised to meet the meta-requirements
Design Product Hypotheses	Used to test whether the meta-design satisfies the meta-requirements
DESIGN PROCESS	
Kernel Theories	Theories from reference disciplines that govern the design process
Design Method	Description of procedures for artefact construction
Design Process Hypotheses	Used to test whether the design method results in an artefact consistent with the meta-design

The framework has already been used to develop design theories for, amongst others, Executive Information Systems (EIS) [46], Decision Support Systems [22], Group Decision Support Systems [27], Organisational Memory Information Systems [43], Simulation Systems for IS Evaluation [15], and Emergent Knowledge Processes [28]. The following section presents the proposed design theory for PIS.

3 A Design Theory for Pervasive Information Systems

3.1 Meta-Requirements Elicitation

The first meta-requirement refers to the profile of prospective PIS users. In the PIS context it is highly unlike for the system designer to know in advance the types of people who will be using the system. Take into consideration the users of the different implementations of tour guides existing in the PIS literature [1, 5, 6, 11]; users may range from people that are vaguely familiar with IT (mainly due to their interaction with commonplace IT artefacts such as mobile phones) or (at extreme cases) techno-phobic. Moreover, these types of users are opportunistic in the sense that they will use the tour guides for a particular time frame and for a particular reason (in this example, to augment their visiting experience). To this end, it is highly unlikely that these users will be subject to thorough training in the system's use as in the case of DIS users. Conclusively, a PIS instance should support all the different user types by employing sufficient mechanisms that enhance or facilitate user interactions with the system, while at the same time haste users' learning curve for using the PIS.

The second meta-requirement refers to the PIS capability to support the multitude of different device types that may participate in the pervasive environment. [18] distinguish among four types of devices: information access devices, intelligent appliances, smart controls, and entertainment systems. Nevertheless, ideally a PIS should support any device that has built-in active and passive intelligence. Therefore, devices' heterogeneity is the most important element that should be addressed during the design of a PIS. Moreover, the plurality and diversity of pervasive devices

generate additional system requirements in terms of connectivity and integration between them [40]. Furthermore, the design of the application and user interface should take into account the unpredictability of end devices. In the case that an application follows the user and moves seamlessly between devices, it is implied that this application will have to adapt to changing hardware capabilities (different types of pointing devices, keyboards, network types, and so on) and variability in the available software services [3].

Designing for manipulation of contextual information, implies that a PIS should be able to perceive relevant information of its environment (with location sensitivity and user identity capturing being the minimum requirement as stated by [2, 12], process it, and adapt to changes in the environment taking into account both historical and current data. Although at present contextual information refers mainly to the users' current location, we expect that in the near future PIS will be able to perceive simultaneously multiple stimulants that may be contradictory one to the other. Thus, this meta-requirement suggests that PIS should accommodate an appropriate mechanism that will filter the different contextual information particles, process them, and adjust their behaviour according to the information that best suits the current occasion.

The final meta-requirement suggests that pervasive artefacts should be 'gracefully' embedded in the physical space. This smooth integration does not suggest that these IT artefacts should be completely invisible to the system users, as implied by most visionary research papers in the field [33, 41, 49, 50]. On the contrary, we follow [37]'s considerations that pervasive technology should be governed by *meaningful presence*, promoting unobtrusiveness. Thus, the challenge is to design PIS in such a way that users perceive them as *part of the environment*. Universal design principles [44] may be applied to create remembrances allowing for system usage with the minimal distraction. Likewise, the PIS designer should also focus on the aesthetical qualities of the pervasive artefacts [13].

3.2 Meta-Design Elicitation

The first meta-requirement clearly suggests that PIS should support opportunistic or inexperienced users that do not have the luxury, or time, for training to the system's functionality. To this end, PIS designers should devise means that facilitate the interaction of such users with the system, and minimise its learning curve. The solution to this problem is to employ *natural, easy to use and easy to learn interfaces* that facilitate a richer variety of communications capabilities between humans and computation artefacts. At the same time, PIS designers should expect that the cases of PIS misuse will be increased compared to DIS. This is the result of the potential PIS users' profile (lack of experience and/or sufficient training). Consequently, the system design should incorporate appropriate mechanisms that minimise the degree of errors, or guide the user in such a way that prevents errors from even occurring. Finally, PIS should be able to perceive users' current skill level through both the contextual information and current system usage and adapt their functionality accordingly.

The diversity and plurality of pervasive devices poses new challenges for information delivery applications in this environment. To meet the demands in this heterogeneous environment, it is necessary for the information to be customized or

tailored according to the user's preferences, client capabilities and network characteristics [19]. As such, PIS should incorporate a sufficient adaptation system that can accommodate all different types of adaptations between different formats. Already several such mechanisms have been proposed in the literature [8, 14, 17, 26, 30, 35] providing the system designer with the option to select the most appropriate for its system requirements. Moreover, a PIS should be scalable. Scalability refers to the ability to incrementally increase the abilities of a system, whilst maintaining, or improving, performance [40]. As such, the issue of scalability refers mainly to ensuring smooth and unobtrusive communication among PIS clients and backend hardware infrastructure (such as sensors and actuators, backend systems, and so on).

Contextual management implies that sensing artefacts should be able to effectively communicate the information they collect and process as well as trigger events that deem necessary to support PIS users. Opposed to DIS where the user initiates the interaction with the system, the PIS vision for invisibility and unobtrusiveness suggests that the system is always active, continuously collecting contextual information, and pro-acting (rather than re-acting) to the needs and demands of the end users before they even start expressing them. Conclusively, the PIS designer should devise an appropriate mechanism that supports proactive system operation. Similarly, since it is extremely difficult to program each participating device and application in the pervasive environment to receive and communicate uniformly the information it collects, PIS designers should devise a representation format that is efficient enough to model, process and communicate context.

The final two meta-design considerations stem from the requirement of smoothly embedding the pervasive artefacts to the physical space. On the one hand, PIS should be easily accessible. If designers follow the extreme suggestion to completely hide the IT infrastructure, we might end up with a system that is completely inaccessible due to the fact that users are unaware of how to use it or, at extreme cases, of its existence. On the other hand, pervasive artefacts should be smoothly embedded in the physical environment. As such, PIS designers should make sure that the systems which they create do not conflict with or challenge the architecture of the place they will be integrated. To reach that goal, co-operation between two previously completely different disciplines (namely IS software engineering and civil architecture) seems to be the logical solution. Consequently, the design of PIS should exploit the existing material of the physical environment and gracefully embed IT in the physical world.

3.3 Design-Method Elicitation

The first design method consideration suggests that PIS designers orchestrate the design around the informal and unstructured activities that users perform. This is also illustrated in the functionality of various PIS implementations. For example, domestic PIS, in their multiple instantiations, support such activities as home automation (inventory management, light and heat adjustment, and so on), or home entertainment. The focus on activities, as opposed to tasks, is a crucial departure from traditional HCI design. Of course, activities and tasks are not unrelated to each other. Often an activity will comprise several tasks, but the activity itself is more than these component parts. The challenge in designing for activities is encompassing these tasks in an environment that supports continuous interaction.

The second design method consideration suggests that prototyping through its various forms (sketching, low-fidelity designing, and mock-ups, just to name as a few) should be a core activity of the design process. Demonstrating prototypes to the system users will ensure the implementation of user-friendly interfaces, as well as the incorporation of user feedback regarding several dimensions of the system such as usability, functionality, privacy protection, and so on. Moreover, since PIS have significant impact to the physical environment (through the embedment of several pervasive artefacts), prototyping may assist designers to fix functional user requirements without implementing the PIS on a full-scale basis, thus, minimizing implementation costs in terms of time and financial resources.

The third design method consideration suggests integrating conceptual design in the early phases of the design process. Contextual design (CD) may be used in the form of sketching or conceptual scenarios to demonstrate the system's functionality to the system's stakeholders. Given that PIS may re-engineer the way users perform their tasks and activities, CD may be employed as a technique that presents alternative usage scenarios, technological solutions, or interaction techniques, so that system users may evaluate them, and select the most user-friendly or appropriate, meeting their goals and aspirations.

The fourth design method consideration aims at addressing issues relating to user privacy. Indeed, context-awareness implies that the system will be able to monitor and process personal information such as the users' current location, activities, even information related to the human body (e.g. users' temperature, heartbeats, or respiration levels). Combining these features with the capability to store this information for future utilisation, it is not surprising that privacy protection is considered as one of the most major properties that a PIS should take into consideration from the very beginning of the design process with many researchers proposing specific guidelines or models that may be applied [4, 7, 20, 25, 34].

Finally, the design of PIS should not be the concern of software engineers only. Software engineers have the necessary skills to analyse and design a system from an IS perspective: create entity-relationship diagrams, data-flows, large databases, select the most appropriate technical solution to the given problem, and so on. Therefore, they, most probably, lack the necessary skills to apply their design solution to the physical space on an effective manner, not to mention to propose the most effective solution based on the design problem. As such, the design team should be enriched with additional members that may involve types of people such as architects, or internal decorators, each providing a different perspective to the design of PIS. These people should be involved from the early stages of the design process in order to counsel software engineers on how to exploit environments' smart spaces. Likewise, they may advise them on how and where to place pervasive artefacts in an unobtrusive, aesthetical, and possibly invisible, to the system users', manner. Finally, they may recommend alternative layout propositions regarding the effective exploitation of the physical space in order to minimise hardware placement and environment restoration costs.

4 Conclusions

This position paper outlined the components of a design theory for the development of PIS. The theory consists of a set of meta-requirements, a set of meta-design considerations, and a set of design method considerations. This research stemmed from the lack of a consolidated framework to guide the design process of PIS. Our intention in this paper is to present the constituting components of the proposed design theory. As such, activities related to the validation of the design theory are beyond the scope of this position paper, nevertheless we will briefly discuss them in the following paragraphs.

Because ISDTs propose theoretical contributions [45, 46] we need to empirically test their propositions. Only the accumulated weight of empirical evidence will, in essence, establish the validity of any design theory without any doubt. In our case, the proposed design theory has been employed for the design of a Pervasive Retail Information System (PRIS). Specifically, we followed the theory's prescriptions to design and implement a PIS capable of enhancing the shopping experience in supermarkets. The detailed design of the pervasive system has been published in [39]. To validate the propositions of the design theory we have generated a set of validation hypotheses measuring the instance's value and acceptance. To assess them, we organised a field experiment in a Greek supermarket (ATLANTIK) where the PRIS was used by supermarket shoppers to conduct part of their shopping. All research hypotheses have been validating which indicates that the proposed design theory results to valuable and acceptable PIS instances. The field experiment results concerning the system's value have been published in [23]. The field experiment results concerning the system's acceptance are available at [24].

The value of this research will be determined by the application of the proposed design theory by other scholars, in their effort to design PIS instances. We believe that this research provides an aggregated approach to describe PIS characteristics and prescribe their development. Moreover, it represents the only consolidated approach, to our knowledge, that investigates the problem of PIS design. In any case, the proposed design theory aims at specifying generic design principles that should be inherited by PIS instantiations. We decided to follow that paradigm in order to ensure that the proposed design prescriptions are applicable to all PIS instances, irrespective of their application domain. It is up to the PIS designers to interpret and apply these prescriptions based on their design problem.

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