Towards a Design Space for Ubiquitous Computing

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Abstract. The purpose of this paper is to illustrate the use of design space analysis for structuring the state of the art in a selected domain. The resulting design space was created based on a literature review and is an analytical tool that can help interaction designers identify the goals, characteristics, challenges, enabling technologies, and quality attributes that are relevant to the design and development of ubiquitous computing systems. This paper describes the procedure of selecting the design space categories, provides examples of using the design space, and discusses the limitations and perspective.

Keywords: Ubiquitous computing, design space analysis, design rationale.

1 Introduction

Over 20 years have passed since the publication of Mark Weiser's seminal article on ubiquitous computing [13]. While the technical solutions necessary for the creation of ubiquitous systems already exists, the design community is still lacking robust analytical tools devoted to the field. Currently design issues are being solved on a case-by-case basis in small teams, where members are able to sufficiently easily convey their ideas [3]. Yet, as the field matures, so do the requirements for analytical tools that can support the design and development process.

The design space proposed in this paper aims to help ubicomp interaction designers to better understand the potential design options and reasons for choosing them, as well as find suitable approaches to solving their particular design challenges within the space [8].

Following is a description of the procedure of constructing the design space, an overview of the main concepts, examples of the potential ways of using the tool, and a discussion of the limitations and perspective.

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2 Procedure

The ubiquitous computing design space is a result of a literature review, which was triggered by an attempt to answer the question "What constitutes the field of ubiquitous computing?" Additional questions were related to the main challenges, issues, focus areas, and technologies being used. The article on "Visualizing the research on pervasive and ubiquitous computing" by Zhao and Wang [14] provided a starting point for the review, as it described a meta-analysis of papers published between 1995 and 2009 on the topics of ubiquitous and pervasive computing. The article provided an overview of key researchers, highly cited papers, as well as keywords related to the main research foci in the field.

A search for articles was conducted through several online digital libraries, mainly ACM Digital Library, IEEE Computer Society, and SpringerLink, as those were the resources accessible in Tallinn University. Additional search was done using Google Scholar. A combination of keyword search and backward searches was used [7] to find articles published in international peer-reviewed conference proceedings and journals. The articles were selected based on the titles, abstracts, and keywords, as well as the fact that the articles themselves were being cited in previously read publications.

While the analysis of articles facilitated the exploration of certain directions in depth, using the Amazon.com search with the keyword "ubiquitous computing" helped select several books, which provided an overview of the historical development of the field, a description of relevant research methods, directions, and undertaken research projects, thus adding a dimension of breadth. The selected publications included those by Krumm et al. [4], Poslad [10], Kuniavsky [5], Dourish [1,2], and Greenfield [3]. The criteria for selecting these books was based on customer ratings and reviews, the titles being cited in previously read articles and books, and reading the introductory sections.

During the work on the literature the initial list of questions was expanded to include those related to finding out what goals ubicomp designers set, what challenges they try to solve, what technologies they use to bring their ideas to life, and what quality attributes they focus on in their designs.

The notes collected from the readings were combined into several clusters, such as characteristics, enabling technologies, and design issues. Further, 18 projects were selected from the readings, which spanned a period between 1992 and 2013 and provided a glimpse of the development of research agendas over the two decades since Weiser's seminal article was published. The publications used for identifying the relevant research projects were those by Krumm [4] and Rogers [11,12]. An additional rationale for selecting these particular projects was that they addressed a spectrum of issues and challenges that ubicomp designers attempted to solve. An initial step was to provide a brief description of each project and attempt to characterize it with the concepts identified previously. This was an iterative process during which new concepts were added, while several existing ones were merged and removed. The result was 5 main categories and 31 subconcepts. The main categories are: characteristics, enabling technologies, design challenges, design goals, and quality attributes. The sub-concepts for characteristics are: invisibility, calmness, embeddedness, context-awareness, mobility, wearability, connectivity, and tangibility. The sub-concepts for enabling technologies are: displays, multimedia, alternative forms of input, low-power high-performance processors, communications, web technologies, machine-readable data formats, sensors, physical object identification, haptics, and databases. The sub-concepts for design challenges are: understanding user needs, designing for multiple interfaces, designing for smartness, selecting appropriate technologies, and developing ubicomp design conventions. The sub-concepts for design goals are: augmenting existing practices, creating engaging experiences, and creating technological infrastructure. The sub-concepts for quality attributes are: usability, accessibility, privacy, and security.

The main categories and sub-concepts were further structured by following an approach proposed by Maclean et al. [9], which uses a semi-formal Questions, Options, and Criteria notation for representation. The Questions refer to the important dimensions in the design space, Options provide possible answers to the Questions, and Criteria argue for or against the Options. In some cases Options can also lead to subsequent Questions, which help to elaborate specific details of the design [8].

By following the selected approach Questions were formed based on the main categories. The 5 Questions were: “What are the characteristics of ubiquitous computing?”, “What are the ubiquitous computing enabling technologies?”, “What are the ubiquitous computing design challenges?”, “What are the ubiquitous computing design goals?”, and “What are the quality attributes of ubiquitous computing?”. The sub-concepts were used as Options for the corresponding questions. The Criteria were formed as explanations for each of the Options. Finally, the Criteria were linked to the Options through positive or negative connections based on their underlying relationships.

3 Visualizing the Design Space

As a result of applying the QOC notation the design space is visualized as node-and-link diagram where the relationships between the elements are illustrated with lines acting as links between Questions and the corresponding Options. Options are linked to corresponding Criteria with either a full line, which signifies that a Criteria argues for the particular Option, or with a dashed line, which signifies that a Criteria argues against an Option [9].

However, as Maclean et. al [9] point out, this approach to visualizing the design space is suitable for diagrams with a limited amount of nodes, as larger diagrams can quickly become messy and difficult to manage. To address this limitation a tabular form can be used (an example is shown in Table 1) where the connections between Options and Criteria are specified with “+” and “-” signs [8].

Table 1. A fragment of the design space for the ubiquitous computing design challenges presented in tabular form

Q: What are the design challenges?	C: Improving ease and convenience of use	C: Facilitating interactions with a wide variety of devices	C: Increasing user control in the interaction	C: Selecting technologies appropriate for the design task	C: Developing a robust design practice
O: Understanding user needs	+	-	+	+	+
O: Designing for multiple interfaces	+	+	-	+	-
O: Designing for smartness	+	+	+	+	+
O: Selecting appropriate technologies	+	+	+	+	+
O: Developing ubicomp design conventions	+	-	-	+	+

4 Examples of Use

Identifying the Options having the most positive Criteria suggested what a potential ubiquitous computing system could be. According to the findings a ubicomp system could be foreseen as a connected solution enabled by web technologies, machine-readable data formats, and physical object identification technologies, aimed at creating engaging experiences with a focus on privacy and security of stored information. The design challenges needing to be addressed are designing for smartness and selecting appropriate technologies.

A similar analysis, focused on identifying the Criteria with the most positive connections to Options, lead to the conclusion that ubicomp interaction designers should turn their attention to providing access to information resources while improving ease and convenience of use and ensuring users' safety and well-being, making them proactive by facilitating new interaction scenarios while also embracing existing social boundaries and conventions, and selecting technologies appropriate for the design task that can provide rich means for creating applications and services.

In addition, the ubiquitous computing design space was recently used in the LearnMix project [6], which aims to re-conceptualize the e-textbook as a collection of professional and user-contributed content available on a wide variety of devices. In this case the selection of Options was based on the project design values, which were informed by the insights from recently conducted ethnography and Delphi studies. The design values used where: integration with existing artifact ecology; sustainability; good user experience; and support for new educational scenarios. A concept map was produced to provide specific examples of related concepts as the initial design values were too general.

Further, the design values and the Options from the ubiquitous computing design space were put into a table and a 3-point scale was used to rank Options based on the design values. 1 point was assigned if the Option had no relation to the design value, 2 points - if having the Option would be useful in the project, and 3 points - if the Option was considered very important to have. Finally, averages were calculated to identify the Options, which were ranked the highest. An example of the ranking is shown in Table 2, where the highest ranked Option is "Understanding user needs".

The results of the ranking suggested that in the context of the LearnMix project it is important to focus on designing a system reliant on embedded infrastructure, enabled by multimedia, alternative forms input, low-power high-performance processors, communications, and web technologies. The main design challenge is to understand user needs with a goal of augmenting existing practices and with attention to usability.

Table 2. Ranking design space Options based on the project values

Q: What are the design challenges?	D: Integration with existing artifact ecology	D: Sustainability	D: Providing a good user experience	D: Supporting new educational scenarios	Average
O: Understanding user needs	3	2	3	3	2.75
O: Designing for multiple interfaces	3	1	3	3	2.5
O: Designing for smartness	2	2	3	2	2.25
O: Selecting appropriate technologies	3	2	3	2	2.5
O: Developing ubicomp design conventions	1	2	3	1	1.75

5 Discussion

The proposed design space is meant to help ubiquitous computing interaction designers reason about the particular choices they are aiming to make in their project circumstances by presenting different options and criteria for selecting those options. It is important to note that while all options have a certain number of criteria arguing for or against them, it does not mean that an option with the most positive connections wins [8]. It is up to the designer to select the criteria and options based on a particular context and the aspects of a system that appear to be more important than others.

The design space described here attempts to map the status quo of ubiquitous computing and offer designers a way to explore potential directions while avoiding premature commitment. However, this design space does not intend to provide a definitive answer to all possible issues in the field of ubiquitous computing, as new technology and ideas are constantly emerging along with the changing requirements of users [8].

One approach to improving the selection of base concepts included in the design space can be done by using them to describe existing ubiquitous computing projects. This effort could help identify if the initial concepts are sufficient or whether new ones need to added to more thoroughly describe the projects that are being analyzed. Another possible approach is improvement of the design space through use in actual ubiquitous interaction design scenarios.

6 Conclusion

The ubiquitous computing design space is proposed as a means for helping HCI researchers and practitioners interested in developing ubicomp systems to identify the potential design goals, characteristics, challenges, technologies, and quality attributes suitable for their work.

The analytical tool described here should be matured further by clarifying the concepts and the relationships between them. Additionaly, it can be beneficial to create an interactive application that can enable users to explore the relationships between different Options and Criteria in an interactive way. Still, we hope that the proposed design space can serve as a step towards producing better ubiquitous computing systems.

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