The Emergence of Wearable Space: A Review and Research Implications

Marios Samdanis
Kent Business School
University of Kent
Canterbury, UK CT2 7PE
ms710@kent.ac.uk

Yikyung Kim
School of Culture Technology
KAIST
Daejeon, 305-701Korea
danza@kaist@ac.kr

Soo Hee Lee
Kent Business School
University of Kent,
Canterbury, UK CT2 7PE
s.h.lee@kent.ac.uk

CHI'13, April 27 – May 2, 2013, Paris, France.

Abstract
This review paper aims to explore the concept of wearable space and identify research opportunities in HCI field. Wearable space is a ubiquitous technologies' environment which through wearable and spatially embedded interfaces links the human body to architectural space. By reviewing more than 60 papers from CHI proceedings since 2007, we analyze wearable space as a series of interactions between: (1) user's body and wearable interface (re-embodiment), (2) wearable interface and spatially embedded agents (disembodiment) and (3) spatially embedded agents and the body (embodiment). Finally, we discuss whether and to what extent recent and current HCI research can realize the vision of wearable space.

Author Keywords
Wearable space; wearable interface; spatially embedded interface; re-embodiment; disembodiment; embodiment

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Documentation, Theory

Topic	Well below	On track	We are there	Exceeded
Wearable Computer Systems				◇
Garment Integration			◇	
Displays	◇			
User Interaction		◇		
Case Studies & Applications		◇		
Augmented Reality		◇		
Networking				◇
Context Awareness			◇	

Table 1. Have we made the technologies of the ultimate wearable computer?

Source: Bruce (2012)

Introduction

In 2012, Bruce coined the question if computing society has 'achieved the ultimate wearable computer' [5]. By reviewing and evaluating eight key technologies which are supposed to compose the ultimate wearable computer, Bruce concluded that computer engineers are doing well in all categories except from 'display', which represents the wide adoption and development of wearable computers as consuming products (Tab.1). In particular, what captures our interest in table 1 is the gap between the successful development of technologies and the actual exploitation of wearable experiences through displays.

However, the purpose of this paper is not to find out ways to commercialize wearable computers, but to coin a similar question in relation to a much more abstract concept: the wearable space. While wearable space or the computer-mediated and ubiquitous connectivity of the body with architectural space has been envisioned since the 1970s, there are few 'displays' of the wearable space that verify its fulfillment.

Instead, HCI has developed a series of technologies that generate interactions around the concept of wearable space. Thus, we question to what extent these technologies have been inspired by the vision of wearable space, or created technologies which indirectly contribute to wearable space, considering that "wearable space emerges out of the interlacing of body and architectural space" [33: 183].

The common vision of architecture and wearable technologies is based on their ability to interact as digital devices. Oosterhuis [33:43] describes future architecture, where "all building elements will behave like intelligent agents", recognizing users and one another. In this context, wearable interfaces are embodied intelligent agents that constantly "transmit and receive emotions, experiences, and meaning" [44:12]. Wearable space is about the connection of the body with architectural space, enabling the build environment to become "an organically possible extension of ourselves" [51:47].

Furthermore, architecture and wearable technologies share an interrelated future. Modern architecture aims to make "visible the hidden geometry of electronics" [51:36], while wearable technologies and "new textiles are changing how the body interacts with its surroundings and how designers and architects are fashioning the built environment" [38:7].

Hansen [12] in his book bodies-in-code explores Danielewski's concept *House of Leaves*, a fantasy space which is able to reconfigure and transform itself to an infinite number of combinations, so that the interior is much 'bigger' that the exterior. In this creative exploration, wearable space emerges as a novel possibility of interaction between the embodied conditions of the wearer and the spatial environment. The body, through the wearable interface becomes part of architectural landscape, extending to digital dimensions.

According to Hansen [12:177], wearable space is mainly an architectural challenge: "…architecture must reconceive its function for the digital age: as the art of framing *par excellence*, it must embrace its potential to bring space and body together in the creation of the 'wearable space'". However, current research in HCI and architecture underpins a state of embodiment

which does not incorporate wearable interfaces. Our intension is to investigate whether this trend is a missed opportunity, or an intentional decision.

The concept of wearable space departs from the overlapping concerns of wearables and spatially embedded interfaces. This paper argues that wearable space is composed by two types of interaction: re-embodiment [12], which considers wearable interface as a digital extension of the human body and disembodiment, which digitalizes embodied information activating action on spatially embedded interfaces. Wearable space can be spatially dispersed, fulfilling the vision of Weiser's vision of ubiquitous computing that links the human body with a technologically enhanced spatial environment.

This research aims to examine two key issues: (1) to what extent current technologies realize the wearable space and which interactions compose the wearable space? and (2) how wearable space is actually explored by HCI experts – is Hansen's vision of *House of Leaves* a representative conceptual model, or are there any other ways that lead to the wearable space?

Method

This study reviews 60 papers which have been presented in CHI conference and are directly or indirectly related to the concept of wearable space. Content analysis is the key method used in order to detect and analyze relevant papers. For this purpose, 'wearable', 'architecture' and 'space' were the three main keywords used to identify relevant papers. In particular, there are three categories of papers identified in this study: (1) papers that present applications on the wearable space, without however mentioning it as wearable space; (2) papers that include one of re-embodied, embodied or disembodied interactions without activating the wearable space; (3) marginal papers which rely outside the interactions of the wearable space, however they can theoretically or practically make a contribution to it, expanding its borders.

Definition and Conceptualization of the Wearable Space

Since late 1930s, architect Fuller, considers technology as "an extension of the human nervous system", while Neutra (1954) envisions an architecture where "…inner nerves of the body might deal with the outside, and…outer nerves provided by technological systems reconfigure the body and mind" [51:47].

Wearable space is a ubiquitous environment that emerges on the interaction of wearable and spatially embedded interfaces. In the last decade, an increasing interest on wearable and embedded interfaces has fuelled research in computer engineering, architecture, wearable technologies' design, urban planning or digital art, generating research towards many directions. We argue that wearable space as the space between the wearable interface and spatially embedded interfaces is a promising area of research, which integrates current research towards future HCI implications. The aim of this paper is to define the concept of wearable space linking current research to specific interactions that energize it.

In general, research that focuses directly on wearable space is relatively limited [12], while the vast majority of work introduces implications that fit within the interaction spectrum of wearable space without

Definitions

Re-embodiment (A): the process which realizes the body and the wearable interface as one entity, facilitating 'the extension of the body into other dimensions'.

Disembodiment (B): the process of digitalizing the human body into a 'set of codes entered into a database'.

Embodiment (C): the process through which the body generates informational "objects", such as images, space and events.

Wearable space: a hyper-connected and hypersensitive space supported by ubiquitous computing that 'emerges out of the interlacing of body and architectural space'.

Source: Hansen (2006)

mentioning it. This paper aims to fill this gap first by defining wearable space as an embodied and spatially interactive experience, while categorizing current research in order to reveal patterns and future possibilities.

One indirect approach to wearable space originates from wearable computers' research according to which wearable interfaces function as mixed reality and context aware agents, able to link an embodied experience to spatial effects. Some examples emphasize on a domestic environment, while others consider work environment as a huge area of implications.

A second indirect approach comes from wearable technologies practitioners, who explore the aesthetic qualities of an interactive experience. Wearable technologies' designers enable the wearable space on fashion shows, while there are projects which have experimented with those technologies in performing arts, such as the digital music performance or wearable performance [2].

A third indirect approach emphasizes interactivity from the standpoint of architecture. While architects realize interactivity in spatial environment, they do not really envision wearable interfaces as part of it, but they focus their creative exploitation at the level of embodiment.

Interactivity on the Wearable Space

Wearable space is actualized since clothing and architectural agents have been shifted from static to interactive. While interactive architecture transforms static spaces into interactive, building "upon the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaption within the contextual framework of human and environmental interaction" [10:12], wearable technologies as wearable computers that emphasize aesthetics and functionality, incorporate embedded technologies that transform them into interactive interfaces [44].

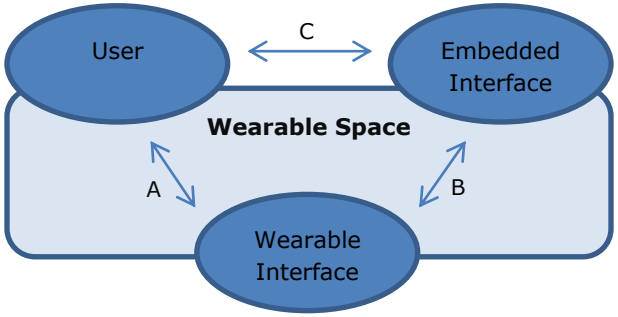

Figure 1. Interactions on the wearable space

Fig. 1 schematizes a series of interactions that enable the wearable space. As a matter of categorization, we draw on new media theory and HCI literature in order to define interactions as: (A) 're-embodiment' as the interaction between the user and the wearable interface; (B) 'disembodiment', as the interaction between the wearable and the embedded interface, and (C) 'embodiment' as the interaction between the user and a digital agent without the presence of a wearable interface. Wearable space [12] has been theorized as a promising area of novel applications, nevertheless its exploration is relatively limited.

Reviewing CHI (2007-2012)

Since 2007, there is an increasing interest in wearable technologies and smart environments. Our target is to identify research on wearable space within the CHI community, and thus an initial observation is that none author is using this term.

Re-embodiment –or the interaction of users with wearable technologies– explores novel uses for the wearable interface (Tab.2). Some projects, such as the leather glove that uses gesture interaction for text input [54] or wearable EOG Googles which detect eyeball movement to move a cursor on a computer screen [6] use embodied movement to generate input. In addition, other projects focus on particular research needs. For instance, face-detection for Asperger syndrome is a wearable camera which aims to capture social behaviour of wearer, such as where he looks at, as well as reactions of people standing in front of him [22].

Furthermore, a certain stream of research considers wearable interface as an extension of human body, operating on mixed reality. For example, a wearable pointing system [31] and WUW project [28] create an augmented reality in which wearables interact with physical objects and demonstrate qualities of other media. A significant amount of research in wearable technologies, such as LiLiPUT [40], Pygmy Ring [32] and hipDisk [53] are designed in order to create playful situations, while DiVA project concerns wearable music performance [37].

Nevertheless, WearIT@Work reveals a significant limitation of wearable technologies [21]. As large scale European project that aims to develop wearable technologies in different working environments, research have concluded that each wearable interface can only achieve a single use that is designed for. Therefore, a future research implication concerns the design of wearable technologies that can accommodate more uses.

Disembodiment –or the interaction between wearable interface and other digital agents– as a single topic is underexplored in CHI, as in this review no papers were identified targeting only to this type of interaction. Perhaps, this shows a research direction in wearables that focuses mostly on re-embodiment, emphasizing fewer interactions with other digital agents. An additional explanation might be that research on wearable space includes disembodiment when exploring explores interactivity with diverse media and not necessarily spatially dispersed agents.

For instance, social resonance device is connected to online social networks and signals discord in wearer's environment [55]; wearable social network [13] communicates embodied information to social networks, while Leung et al. [24] wearable device enables wearable visualization of wearer's online social identity. Thus, disembodiment in these cases considers communication of embodied information from and to social networks, exploring wearable space not as a physical space which is enhanced with digital qualities, but as a mixed reality condition that overlaps between physical actions which are detected and broadcasted by wearable interfaces and virtual reality on digital platforms.

The review in numbers

Total number of papers: 60

Re-embodiment: 13
Disembodiment: 0
Embodiment: 9
Wearable space: 16
Marginal projects: 22

Re-embodiment	**Wearable Space**	**Embodiment**
Leather glove for text input (Witt & Janssen, 2007)	BodySpace (Strachan et al., 2007)	Location-aware computing (Girardin, 2007)
LiLiPut (Reichl et al., 2007)	Complex mobile situations (Klug, 2007)	Ludic spatial interface (Mathew & Taylor, 2008)
Face-detection for Asperger syndrome (Lee et al., 2008)	Wearable computing for fire fighters (Klann, 2007)	BrightShadow (Rekimoto, 2008)
Wearable pointing system (Oakley et al., 2008)	Social resonance device (Wright et al., 2008)	Cyber Pung-Kyung (Park & Nam, 2008)
WearIT@Work (Lawo et al., 2008)	Brainy Hand (Tamaki et al., 2009)	BubbleWrap (Bau et al., 2008)
Wearable bracelet detects EMF (Vaucelle et al., 2009)	Wearable social network (He & Schiphorst, 2009)	Shade Pixel (Kim & Lee, 2009)
WUW Wearable Gestural Interface (Mistry et al., 2009)	Ubiquitous Drums (Smus & Gross, 2010)	Mouseless (Mistry & Maes, 2011)
Wearable EOG Googles (Bulling et al., 2009)	Communiclay (Raffle et al., 2011)	SPARSH (Mistry et al., 2011)
Gesture watch (Lee & Starner, 2009; Dean et al., 2010)	Wearable device and social identity (Leung et al., 2011)	Speech@Home (Brush et al., 2011)
Wearable objects for mobile audio device (Kim et al., 2010)	ActivMON (Burns et al., 2012)	
DiVA for performace (Pritchard et al., 2011)	EyeRing (Nanayakkara et al., 2012)	
Pygmy Ring (Ogata et al., 2012)	Arm hand training after stroke (Beursgens et al., 2012)	
hipDisk (Wilde et al., 2012)	Synthetic space (Takeuchi, 2012)	
	TeleWEAR (Taylor et al., 2012)	
	Touchbox (Hobye, 2012)	
	Wearables for nomadic musician (Kock et al., 2012)	

Table 2. A review of wearable space

This review demonstrates that exploration of wearable space concerns a space between wearer and different digital media. Except from social networks, these media include music players which are controlled through gesture, such as in the case of BodySpace project [47] or they can be other mobile media which function on complex environments, such as an urban context [19].

Marginal Projects

- Design systems to design themselves (Schweikardt & Gross, 2009)
- Evolvement Organic User Interface as embedded agents (Coehlo et al., 2009)
- Buddy Bearings: person-to-person navigation system (Hayes et al., 2010)
- BIS*i*: a blended interaction space (Paay et al., 2011)
- Digital Habitat (Pohjola, 2011)
- Designing for movement experience (Levisohn, 2011)
- Digital materiality and form-driven interaction (Jung & Stolterman, 2011)
- Safety in urban context (Satchell & Foth, 2011)
- Ar-CHI-tecture (Dalton et al., 2012)
- Moodcasting interface (Stangl et al., 2012)
- Smart high end homes (Lynggaard et al., 2012)

In addition, Klann's [16] project on wearable space reveals specific practical implications for fire fighters. In this case, wearable space is an operational space that allows better control and coordination of firemen, detecting their position, as well as receiving input of the situation from cameras worn by them. This project permits distant vision of both firemen, who receive real-time information from coordinators, while coordinators can receive more information about the situation as firemen stream data from the wearable interfaces.

Communiclay [39] is an additional project of distant connectedness through the wearable space. In particular, Communiclay enables kinetic learning and tangible kinetic communication, wearing the system with a partner as sensor/actuator exoskeletons. In this case, the wearable space is the space between two or more people, as movement is transmitted through the wearable interface.

In general, current research on wearable space explores more of the possibilities of connectedness between users than interactions between wearable and spatially embedded interfaces. For instance, ActivMON project is a wearable wrist device that connects users' individual sport activity using an ambient display. The result of this device is a sense of group exercising and motivation despite the fact that users practice individually.

Applications on wearable space are designed to assist specific situations. For example, EyeRing is a wearable device aiming to assist visually impaired people [30]. Wearable interface is finger worn assistant which retrieves spatial information as the user points to objects and space, receiving information on an earpiece. Moreover, wearable space applications are designed for rehabilitation purposes, such a wearable device that monitors the progress of hand moving after stroke and uses play to motivate to practice more.

Perhaps the closest project to Hansen's vision of wearable space is Takeuchi's [49] synthetic space. Synthetic space takes place as wearable interfaces interact with interior architecture. In this case, architectural space is fused with digital properties, enabling change of the surrounding of built environment with the ease of changing wallpaper on a computer. Especially, virtual walls' application operates based on wearable devices, creating a fluid space that sonically isolates some users in a room. Virtual walls can also affect visual characteristics of space, allowing users to have different visions of space within and beyond virtual walls.

Furthermore, research on wearable space can generate service applications. TeleWEAR [50] is a service application of the wearable space for older people security. Especially, this project engages users in product design, highlighting the need to co-create the product.

Finally, some projects explore wearable space as a playful space between users and other people. For instance, Touchbox is a wearable application that enables different sounds, as the wearer is touching other people [15]. Similarly, wearable for nomadic musicians is a wearable device designed to record a music idea, in case musicians are away from their instruments [20].

Papers on embodiment and marginal projects might illuminate the reason why current research on wearable space does not explore spatially embedded interfaces. Embodiment –or the interaction between the embedded agents and the user– as explore within CHI does not require wearable interfaces. In general, research on embodiment is divided to two categories: on one hand, embodiment explores embodied interaction with digital agents. For instance, BrightShadow project detects shadow movement in space [41]; Mouseless enables cursor control by gesture without the use of mouse; SPARSH enables copy-paste between devices by just pointing a finger from one screen to another [27] and Speech@Home enables devices' control using voice [4]. On the other hand, embodiment experience results from the interaction of spatially embedded devices with the conditions of real or virtual environments. For instance, ludic design promotes "an engagement through embodiment – situating the user in the context of the design where the information is not necessarily clear but derived from a situated context" [26:2534]. Cyber Pung-Kyung [36] is an ambient device that streams and broadcasts embodied information from virtual worlds to physical objects.

Nevertheless, marginal projects that explore digital technologies rarely consider wearables as a digital agent. For instance, BIS*i* is a blended interaction space for teleconference [34]; Digital Habitat connects different embedded agents at home [35]; safety in urban context debates issues such as surveillance and private in the networked world [42]; project Ar-CHI-tecture recognizes the importance of agency however it explores interactivity between environmental conditions and embedded agents [9]; and Smart high end homes considers the existence of smart devices [25]. Clearly, wearables go beyond the considerations of architects that explore digital media, and thus, this can be a future research prospect.

Nonetheless, other marginal projects, such as Buddy Bearings [14] or Moodcasting interface [46] use mobile devices and affective media to capture and broadcast information, instead of using wearable interfaces. Considering the convergence of wearable with mobile devices, projects like these can apply using wearable interfaces.

Conclusion, Research Limitations and Future Implications

This paper has reviewed 60 CHI papers over the period 2007-2012 in order to identify the current status of wearable space research. This review by focusing on different types of interactions that occur on wearable space has identified current trends, unexplored areas and fertile implications for future research.

Although wearable space is conceptualized in theory as an interactive space between wearable and spatially embedded interfaces, actual research explores a variety of media, such as mobile media or social networks among others. While wearable space in theory aims to link user to architectural environment, actual research on wearable space investigates the possibilities of connectedness mostly between: users and other users, users and social networks, users and computers. Wearable space enhances visual and in some cases sonic perspectives of spaces for operational and practical needs. Only in few cases wearable space has been envisioned as fluid architectural space that overlaps with wearable technologies.

Future research can also investigate different possibilities of disembodiment using diverse media. In addition, research on disembodiment can consider research areas, such as machine-to-machine communication and internet of things, illuminating the relationship between different digital agents.

Despite the fact that wearable space has been explored from diverse ways, the perspective of architecture is relatively limited. As we identify in this review paper, projects that concern architectural implications do not consider wearables as an agent of interactivity, and as a result none of them consider the possibilities of the wearable space. Therefore, an emerging future research implication considers wearable space as an interdisciplinary field that integrates interactive architecture and wearable technologies' design.

Nonetheless, this research faces particular limitations, which can be subject of future research. One of them concerns research design, as this review paper only includes CHI archive. Additional sources from different conferences and communities may illuminate the issue of wearable space, coupling alternative perspectives. An additional limitation of this study concerns the scope of this review paper. Here we have examined 60 CHI papers in order to find out how wearable space is explored in actual research. So, future research can go beyond this descriptive point, understanding critical issues that illustrate the design for wearable space.

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