THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Body-Centric Projections

Spatial projections relative to the body for map navigation

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CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2016

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Photograph depicts a pilot study participant, Nicolas Weber, performing map navigation with a mid-air display during a pilot study. The picture was taken by the author and reproduced with consent.

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Abstract

Technological advancement has led to the steady improvement of brightness and decrease in size of pico projectors. These small devices are available as stand-alone projectors for personal use or are embedded in consumer electronics, ranging from smart phones, smart glasses, to video cameras. Portable projected displays provide opportunities in creating feasible, desirable, and viable wearable devices that present information.

The main contribution of this thesis is to develop and evaluate a set of working prototypes that present information in new ways around the human body for the task of map navigation. Based on experiments using these prototypes, we gain insights and present a design space for mobile visual interfaces from a body-centric human-computer interaction perspective.

First, we design interfaces for an architectural application involving environment projection and explore reconstruction of physical surfaces in different contexts. Environment-centric projection is employed to create interfaces in which the user is performing tasks inside a limited physical space augmented with information.

Second, we explore the placement of information around the human body while cycling and walking for the task of map navigation in an urban environment. We evaluate these body-centric interfaces through field experiments. Findings from our experiments show that, for instance, while cycling road projection is considered safer and easier to use than a mobile phone, a head-up display is considered safer than a projected display on the road. The implications of display placement could inform the design of visual interfaces for bike design, such as bike sharing systems that are already supporting map navigation using tablets mounted under handlebars. Furthermore, projections on the road could replace headlights to make people more aware of moving vehicles, showing drivers' intentions and the subsequent position of vehicles.

Then, we propose the concept of a "wearable mid-air display", a device that presents dynamic images floating in mid-air relative to a mobile user. Such devices may enable new input and output modalities compared to current mobile devices, and seamlessly offer information on the go. A functional prototype was developed for the purpose of understanding these modalities in more detail, including suitable applications and device placement. Experiment results investigate the use of a wearable mid-air display for map navigation.

Keywords: Body-centric, Projection, Mid-air display, Map Navigation, Reconstruction
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Co-supervisors: Mohammad Obaid (Koc University) , Ulf Assarsson (Chalmers)
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THESIS

This thesis consists of an extended summary and the following appended papers:

Paper A	S. Nielsen, A. Dancu, Layered Subsumption in Intelligent Material Building Systems, Work-in-progress, Demo, 5pg, 8th International Conference on Tangible, Embedded and Embodied Interaction, TEI'14, 2014, Munich, Germany.
Paper B	A. Dancu, S. Nielsen, C. Hedler, M. Witt, A. Pelling, H. Frank, C. Carlsson, M. Fjeld, Emergent Interfaces: Constructive Assembly of Identical Units, alt.CHI Extended Abstract, 451-460 (10pg), CHI'15, 2015, Seoul, South Korea.
Paper C	A. Dancu, M. Fratarcangeli, M. Fourgeaud, Z. Franjcic, D. Chindea, M. Fjeld, Low-cost Experimental Setups for Mid-air 3D Reconstruction, Full paper, 6pg, Smart Tools and Apps in Computer Graphics, STAG'15, 2015, Verona, Italy.
Paper D	A. Dancu, M. Fourgeaud, Z. Franjcic, R. Avetisyan, Underwater reconstruction using depth sensors, Technical Brief, 4pg, Special Interest Group on Graphics and Interactive Techniques Asia, SIGGRAPH Asia '14, 2014, Shenzhen, People's Republic of China.
Paper E	A. Dancu, Z. Franjcic, A. Ünlüer, M. Fjeld, Interaction in Motion with Mobile Projectors: Design Considerations, Full paper, 61-68 (6pg), Pervasive Displays, PerDis '15, 2015, Saarbrücken, Germany.
Paper F	A. Dancu, Z. Franjcic, M. Fjeld, Smart Flashlight: Map Navigation Using a Bike-mounted Projector, Note, 3627-3630 (4pg), Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI'14, 2014, Toronto, Canada.
Paper G	A. Dancu, V. Vechev, A. Ünlüer, S. Nilson, O. Nygren, S. Eliasson, J. Barjonet, J. Marshall, M. Fjeld, Full paper, 151-159 (9pg), Gesture Bike: Examining Projection Surfaces and Turn Signal Systems for Urban Cycling, International Conference on Interactive Tabletops and Surfaces, ITS'15, 2015, Funchal, Portugal.
Paper H	A. Dancu, M. Fourgeaud, M. Obaid, M. Fjeld, N. Elmqvist, Map Navigation Using a Wearable Mid-air Display, Short paper, 71-76 (6pg), International Conference on Human-Computer Interaction with Mobile Devices and Services, MobileHCI'15, 2015, Copenhagen, Denmark.
Paper I	J. Marshall, A. Dancu, F. Mueller, Interaction in Motion: Designing Truly Mobile Interaction, Proceedings of the 17th conference on Designing Interactive Systems, DIS '16, 2016, Brisbane, Australia.

I am the main contributor in paper C, D, E, H. There, I contributed with the idea, prototype implementation, experiment design, evaluation, and writing the paper. The work described in the papers A, B and I combines the different authors' expertise and interests. I contributed with ideas, related work, and writing the paper. The work described in paper F and paper G combines the authors expertise and interests. There, I contributed with ideas, prototyping, experiment design, related work, and writing the paper.

The appended papers (A to I) were re-formatted to match the style of the thesis; the text was not changed in content, only in font type and size, some images were resized or changed in orientation. The references were all separated from the end of the papers and compiled at the end of the thesis.

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Abbreviations

AR Augmented Reality

FOV Field of View

HCI Human-Computer Interaction

HMDs Head-mounted Displays

HUD Head-Up Displays

SAR Spatial Augmented Reality

Part I
Extended Summary

1 Introduction

Humans have access to computational devices at all times – people check their mobile phone 221 times a day [Tec14], while 6.4 billion smartphone subscriptions are estimated by 2021 [Eri15]. The design of current mobile phones determines that users stand still and hold the device in one or both hands [Gol+12]. Personal computers evolved in an office environment in which the user sat down and moved only the fingers on the keyboard, while looking at a screen [OI04]. The body posture during the interaction has shifted from this seated configuration to a physical, more mobile setting. Human-Computer Interaction (HCI) researchers are beginning to design computer interfaces and interactions that put the body and its context into the center of the design process [Wag13]. This is beginning to be reflected in the new visual interfaces such as lightweight smart glasses that employ projection to display information overlaid on the physical world. Smartglasses have different assumptions, form factor, placement, and usage patterns than conventional mobile devices such as mobile phones. This type of *interaction in motion* brings up many challenges and applications that are only beginning to be explored.

While wearable computers and Head-mounted Displays (HMDs) have been researched in the past, the human-centered approach from today aims to present information in ways that easily integrate in people's lives by offering functionality without diverting attention and disrupting actions. To design such interfaces, we need to take into account (i) the current context, physical environment, and the realities of people's lives where information and computation are needed. (ii) the human body and its physical abilities. The context and physical environment of a person are often changing during the day due to its locomotion abilities.

In this thesis, we focus on walking and cycling activities. These methods of locomotion will be two main modes of urban travel considering the latest predictions in urban mobility [LSE15]. Smartphone applications already provide flexible travel solutions as the user moves through the city and map navigation is considered a common task that is regularly being performed. The behavior and expectations of humans have changed with the advent of mobile phones, and people take for granted smartphone applications and usage in their current form. For example, people can be seen walking and cycling while performing map navigation on a smartphone. In the cyclist use case, the task requires the cyclist to look at the phone, pedal, steer, and pay attention to traffic and the road ahead. A commercial solution is phone holders that can be mounted on handlebars and free the hands of the cyclist, reducing task load. This is an example of a need of society satisfied through an interface designed to display information in a manner that may not be safe or easy to use. Interaction Design could improve ease of use and safety taking into account the context of locomotion, the space around the human, and the user's Field of View (FOV).

The concepts and interfaces developed in this thesis provide alternative and novel ways to perform map navigation during locomotion. We developed prototypes using projection and registration that focused on the environment, body and its locomotion abilities.

First, we designed interfaces involving environment projection and reconstruction of physical surfaces in different contexts. Environment-centric projection is employed to create interfaces in which the user is performing tasks inside a physical space augmented with information.

Second, we explored the body-centric placement of information while cycling and walking for the task of map navigation in an urban environment. We evaluate these interfaces through field experiments. Findings from our experiments show that, for instance, while cycling, road projection is considered safer and easier to use than a mobile phone, and a head-up display is considered safer than a projected display on the road. The implications of display placement could inform the design of visual interfaces for bike design, such as the Copenhagen City Bike that supports map navigation on a tablet mounted under the handlebar. Furthermore, projections on the road could replace headlights to make people more aware of moving vehicles, showing drivers' intention and the subsequent position of vehicles.

Next, we propose the concept of a *wearable mid-air display*; a device that presents dynamic images floating in mid-air relative to a mobile user. Such devices may enable new input and output modalities compared to current mobile devices, and seamlessly offer information on the go. A prototype was developed for the purpose of understanding these modalities in more detail, including suitable applications and device placement. The experiment investigates the use of a wearable mid-air display for map navigation.

1.1 Motivation

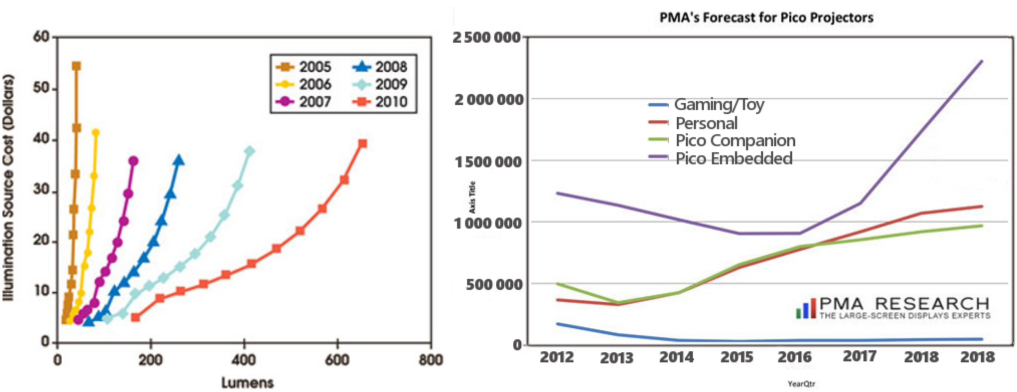

Figure 1.1: *Projector price drop in illumination and increase in brightness [Fis06] (left); Forecast for pico projectors market [Res16] (right)*

The left image in Figure 1.1 shows how illumination cost has decreased and projector brightness has increased significantly in only five years between 2005 and 2010 [Fis06]. The right image in Figure 1.1 presents a forecast with the embedded projector market that is expected to double between 2016 and 2017 [Res16]. Projectors have shrunk in size and decreased in cost, attracting the interest of industry and HCI researchers to develop novel applications and interaction techniques using projection.

The following motivations stand behind this thesis:

Widespread adoption of mobile technology is changing the way we use our body. While 73% of the human population owns a mobile phone, it was reported that in 2014 the average user picks up their phone 221 times a day [Mee13; Tec14]. We should design technology that takes into account our mobile nature and our body, not one that makes us stop and look at a screen that we hold in a hand. Information should be available when we need it without requiring us making extra physical effort.

Stop to interact paradigm The vast majority of systems described as being mobile, whilst they are portable, are in fact designed to be used while stationary, a design called "stop to interact" [MT13a]. In reality people do interact with devices whilst moving [Fri+13], but studies show that mobile phone use decreases safety while cycling [SF13], driving [NR02], and walking [Hym+10].

Increase in urban mobility The total amount of urban kilometers travelled is expected to triple by 2050. Traditional patterns of motorization are changing and interfaces need to be designed for the "increasing number of alternatives, including cycling and walking as main modes of travel". [LSE15]. We develop and evaluate novel interfaces for walking and cycling.

The close coupling between machines and humans has been anticipated since 1960 when it was suggested that *man-machine symbiosis* would facilitate thinking, finding solutions to problems, and making decisions in collaboration with the computer [Lic60]. The computer has dramatically shrunk in size from whole buildings containing mainframe computers inside research facilities to having small computers in our pockets. This accelerated technological development has overlooked human factors and we are at a crossroad today. Biologically, we have evolved as mobile, social creatures. Technologically, we have created small computing devices that we call mobile and which isolate us from our surroundings. We design technology that results in people checking their mobile phone two hundred times a day [Tec14]. Designing for everyday use should result in technology that fits "easily into people's everyday lives, rather than forcing their lives to fit the dictates of technology" [MS07]. As designers of interactive devices, we need to foresee the long-term consequences of the technologies we develop, become responsible, and design technology that supports the mobile, social human.

The current limits of these devices are not computational, but human factors [Bau10]. Mobile phones are not designed to support our mobile nature, they assume we are standing still and holding the device in one hand. Our current mobile devices have a small visual display as input and output modality, with "only a very limited window into ones information space" [Che12].

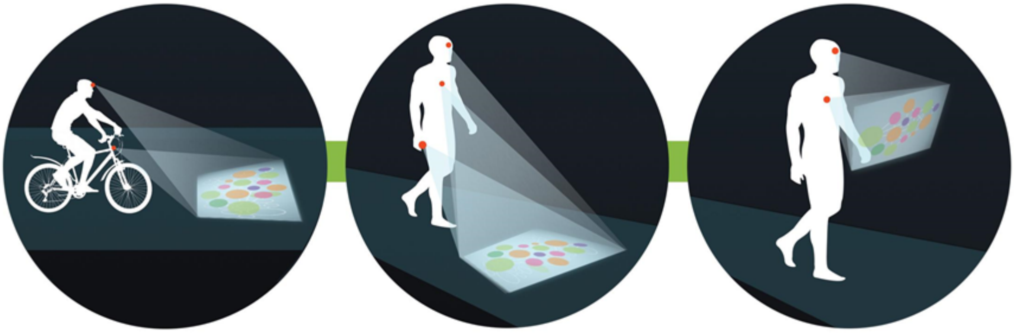

Figure 1.2: *The interfaces proposed for cycling and walking*

1.2 Interaction in Motion

We will assume that by *mobile interactive system* we mean a digital system where those interacting with it are able to perform some kind of locomotion while doing so. How they move is termed the *movement activity*, such as walking or cycling. Active use of a mobile interactive system while moving is *interaction in motion*. Paper I presents a taxonomy and framework based on two key dimensions: relation of interaction task to locomotion task, and the amount that a locomotion activity inhibits use of input and output interfaces. We accompany this with four strategies for interaction in motion that aim to enhance our understanding of what being "mobile" actually means for interaction, and help practitioners design truly mobile interactions.

1.3 Research Questions

The purpose of the research presented in the thesis is to develop novel projection prototypes that augment human capabilities. Since manipulation and locomotion are the main ways we interact with the physical world [MS07], we focused on these abilities in the two parts of the thesis. Table 1.1 summarizes the research questions.

The first part of the thesis designs interfaces focusing on manipulation and environment, with technical contributions in terms of tangible interfaces implemented through projection mapping systems that process physical environment geometry in real-time and align it to interactive projections (papers A, B). The research questions of these architectural applications refer to adaptive, self-adjusting building systems that emerge based on the interaction between the human and the tangible interface (RQ1). Papers C and D explore the topics of environment reconstruction of underwater surfaces and tall structures using a multicopter. Future research directions of these works include mid-air projection, underwater projection, and registering context of use around the human body in dynamic settings.

The second part of the thesis focuses on locomotion abilties and designs body-centric interfaces using projection evaluating them through map navigation applications in

Research Questions	No.	Paper
Part I. Environment-centric projection		
Would coupling block geometry and motor skills lead to interface emergence?	(RQ1)	A, B
Could environment and context of use be registered?	(RQ2)	C, D
Part II. Body-centric projection		
How can body-centric placement of information support map navigation?	(RQ3)	E-H
How to extend peripersonal space with projected information?	(RQ4)	E
Would projections around the body support map navigation?	(RQ5)	E
Does a projected map in front of a bike support map navigation?	(RQ6)	F
Is road projection easier to use than a smartphone for map navigation?	(RQ7)	F
Is the road projection easier to use than a head-up display while cycling?	(RQ8)	G
Could we increase safety through projections around the bike?	(RQ9)	G
Is a gesture-based system easier to use than button input for cycling?	(RQ10)	G
Would a mid-air display with smartphone functions be useful?	(RQ11)	H
Which body parts do users prefer to carry a wearable mid-air display?	(RQ12)	H

Table 1.1: Summary of Research Questions

outdoor urban environments. Papers E – H raise a number of research questions regarding placement of information around the human body while walking (RQ3, RQ4, RQ5, RQ11, RQ12) and cycling (RQ6 – RQ10). Paper E asks whether projected information can extend peripersonal space for the purpose of pedestrian navigation, explores such an interface through two prototypes, and identifies a number of design considerations for interaction in motion with mobile projectors. Paper F enquires whether map projection in front of a bicycle can support GPS navigation and investigates if this prototype would be easier to use than a smartphone mounted on the handlebars. Paper G compares the previous road projection with a HUD and examines a gesture-based turn signaling system and projection around the bicycle for the purpose of increasing safety. Paper H explores the use of a wearable mid-air display investigating the body parts where such a device could be carried in order to support safety and easy to use.

This thesis has the following assumptions:

A1) design for mobility is human-centered; not for rectangular devices with displays

A2) design accounts for the space around the human

A3) design is body-centric taking into account the human body and its physical capabilities

A4) visual perception is the main channel for access of digital information

A5) mobility and locomotion are key to human capabilities [BL04] and needs [NP12]

A6) the interaction, movement, and visual perception of information happens inside a shared common physical space

A7) relevant design factors are found in the complexity of the real world

A8) design for already known tasks and expectations; augment, not automate [Nor09]

A9) design for urban mobility [LSE15; Ron08]

A10) mobile applications should be evaluated through field studies [KS14]

2 Background and Related Work

The background of this work will cover the related research areas of human-computer interaction, interaction design, augmented reality, and tangible interaction, followed by related work on projected interfaces and body-centric HCI.

2.1 Related research areas

The related research areas that are relevant to our work include human movement science, augmented reality, and body-centric HCI.

2.1.1 Human movement science

The two schools of thought established by Fitts and Posner [FP67] and Gibson [Gib50] are important legacies in HCI and inspired our work.

Human performance

We mention the two approaches of human movement science, in which Fitts and Posner coin *human performance* as the analysis of "complex tasks into their simpler components and to establish quantitative estimates of man's abilities in each of the basic functions. In this way, it makes possible predictions about man's capability in performing complex skills" [FP67; MR88], laying the foundations of empirical investigations in HCI. This approach assumes the existence of tasks that require no or minimal attention, such as "walking and talking, or driving (lane keeping) and listening to the radio" [Wic13]. Under single task conditions, if one invests more effort and resources into one task, performance will increase [Wic81]. Under dual task conditions, performance varies in favor of the task that requires most attention. Norman writes that "best way to control resources is to ask subjects to perform two tasks simultaneously. One task is the interfering task. It should require a fixed amount of resource. The other is the primary task. It is assumed to use all the remaining available resource" [NB75].

When evaluating applications for interaction in motion, locomotion could be the primary task, and engaging with information could be the interfering task. Mobile phones have been empirically evaluated in motion for the dual task of walking and reading [Bar+05]. Cognitive load depends on walking speed [Nas+15], but increases significantly during walking while reading or selecting a target on the mobile phone [SR10]. An outdoor study has shown that gait speed was modified in order to maintain typing speed [Plu+15]. For instance, in papers F, G, H, ease of use was assessed during the task of map navigation while walking and cycling.

Ecological approach

The other approach in movement science is based on the close relationship between perception and action argued by Gibson [Gib50]. This approach together with ideas from phenomenology and social computing inspired HCI research, such as tangible user interfaces and embodied interaction (section 2.1.5). One of the early works of Gibson illustrating the "ecological approach" is the perception theory on automobile driving assuming that "driving is a type of locomotion through a 'terrain' or field of space", "psychologically analogous to walking or running, except driving is locomotion by means of a tool" [GC38]. This assumption was explored in paper G by projecting the intention of turning and the concept of safety envelope around the moving bicycle.

2.1.2 HCI, Interaction Design, and Mobile HCI

Human-Computer Interaction (HCI) is defined as "the study and practice of the design, implementation, use, and evaluation of interactive computing systems' ' [SIG16]. Winograd predicted the growing importance of the computing field and the corresponding shift that will take place through Interaction Design: "designing spaces for human communication and interaction will lead to expansion in those aspects of computing that are focused on people, rather than machinery" [Win97]. Preece et. al define Interaction Design as "designing interactive products to support the way people communicate and interact in their everyday and working lives" [PSR15], having a much wider scope than HCI.

Mobile HCI is defined as "the study of the relationship (interaction) between people and mobile computer systems and applications that they use on a daily basis"; more precisely, the study aims at "understanding the users, their various capabilities and expectations and how these can be taken into consideration in the mobile system or application design" [Lov05]. All experiments described in the thesis papers, except paper A and paper B, take place in mobile, outdoor settings.

2.1.3 From Graphical to Physical

The first graphical interface for a computer was proposed by Ivan Sutherland in 1964; Sketchpad offered the possibility of drawing lines and circles directly on a computer screen [Sut64]. In contrast to the traditional way of inputting information by means of a keyboard, Sutherland's approach was to create and modify digital information through sketching; seamlessly coupling human action to pixels, which at the time was a leap in Human-Computer Interaction. Currently, these interfaces are widespread through the adoption of smartphones' touchscreens that couple the sense of touch and the displayed information. However, the environment we inhabit is much more complex than the actions allowed by a flat computer screen. Sutherland envisioned in 1965 the Ultimate Display, a room in which a computer could directly control the existence of matter. This type of display would merge the digital and the physical worlds, dramatically changing how people interacted with computers. [Sut65]. This type of display would not only be confined to the screen of a computer, it would extend to our environment.

Extending the confines of digital information to the physical environment is common practice in the field of Architecture, where in 1979, Robert Aish proposed a new type of computer-aided architectural design process, employing a 3D modelling system able to add and remove blocks of an architectural model and generate a corresponding perspective view of the digital model and a thermal performance plot on a computer screen [Ais79]. It was suggested that buildings could change based on the information gathered from the environment: that architecture could be "responsive to evolving in not just a virtual but a real environment" [Fra95].

The environment complexity and emergence, the tangible interface, and real-time environment registration and projection mapping are the topic of paper A and paper B, presenting architectural applications where the building environment is responsive by projecting real-time information directly onto the blocks of the architectural model.

2.1.4 Spatial Augmented Reality

An Augmented Reality (AR) system "supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world" with the following properties: "combines real and virtual objects in a real environment; runs interactively and in real time; and registers (aligns) real and virtual objects with each other" [Azu+01]. As the AR field grew and encompassed so many technologies and application, Milgram et. al found it necessary to introduce the term "Mixed Reality (MR) environment as one in which real world and virtual world objects are presented together within a single display, that is, anywhere between the extrema of the reality - virtuality continuum" [Mil+95].

The concept of Spatial Augmented Reality (SAR) was proposed by Raskar et. al where digital light projectors were used to render images and virtual objects directly onto the physical space of the user without having the need to wear head-mounted displays [RWF98]. Soon after, the concept of *everywhere displays* was proposed as a service by public infrastructure; a scenario for ubiquitous computing where projectors could be used for displaying graphical interactive displays as opposed to users carrying devices [Pin01]. Spatial projections in public spaces are currently used for entertainment and education in museums, dance and theatre performances, and architectural applications where facades of buildings are transformed through animation. One architectural projection case study was on the second largest administrative building in the world, the Palace of Parliament in Bucharest that was transformed into 23 000 square meter projection space [Pan14]. Later, Bimber and Raskar argued in their book *Spatial Augmented Reality* for taking augmented reality beyond the "traditional eye-work or hand-held displays" by employing technologies such as transparent screens, holograms, and projectors to enable non-mobile spatial augmented reality applications [BR05].

In a 2008 survey on AR [ZDB08] the authors argue that the resolution, FOV, speed, and mobility of HMDs will increase, predicting the market success of low cost ergonomic HMDs. These devices have come to market: the 36g, $1500 Google Glass [Goo12] was released in 2013, while the 579g, $3000 Microsoft HoloLens [Mic16] shipped in 2016. The competition of HoloLens is Magic Leap [MIT15], that gained much funding and popularity through the released videos showing perfect tracking and integration of digital content with the physical indoor environment. The survey authors [ZDB08] also predict the bright future of projection-based displays that could be integrated into the daily environment of the user, supporting mobile or spatial AR with minimal intrusion. A 2010 survey on AR [VP10] categorizes visual displays in video see-through, optical see-through, and projective, arguing that the latter category does not require special eye-wear; eyes can accommodate when focusing and cover large surfaces having a wide FOV.

Papers A, B, E, F, G have employed projection directly on the physical environment combining real and virtual objects in real-time. Only papers A and B align the virtual and real objects. Papers C and D are concerned with reconstruction of the environment and the generation of a 3D model, but registration and visualization does not take place in real-time.

2.1.5 Tangible and Embodied Interaction

Departing from the augmented reality concept popular at the time and embracing Mark Weiser's vision of ubiquitous computing and situated information spaces [Wei91], Fitzmaurice suggested that electronic information should be associated with physical objects in the physical environment, so that "our information spaces will be 3D" [Fit93].

Tangible User Interfaces can be traced back to the work of Fitzmaurice, Ishii and Buxton, proposing that virtual objects could be directly controlled through physical handles [FIB95]. Two years later, Ishii and Ulmer [IU97] proposed the concepts behind Tangible Interaction in which (i) surfaces in architectural space such as walls, desktops, and ceilings are interactive becoming the interface to the virtual world, (ii) seamless coupling of physical objects with digital information, (iii) ambient media such as sound, light, and airflow as digital interface in the background of human perception, similar to Buxton's integration of periphery and context [Bux95]. At the same time, Fjeld et. al [FBR97] developed a projection system as part of an architectural design room where bricks were used for direct manipulation of information and argued as being a natural user interface that extends the concept of augmented reality.

Ten years later, after the field matured, Dourish [Dou04] identified three trends in tangible computing:

- distributing computation across a range of devices in the physical environment that are aware of their location and proximity to other devices (spatial dimension, more on the topic in section 2.4.2)
- augmenting everyday objects with computational power (e.g. pens, paper, cups, toys) so that they are able to respond to their environment and people
- developing methods for creating environments where one can interact directly through physical artifacts.

Based on these principles combined with ideas from phenomenology and social computing, Dourish coins *embodied interaction* that aims to create technology that seamlessly integrates into people's everyday practices, based on human skills and experiences that take place in their world [Dou04; MG15].

2.2 Projection Overview

Figure 2.1 depicts a timeline with projection milestones illustrating the development of this technology, starting with static images projected onto surfaces. Early history of light projection originates from the 2nd century BC where "magic mirrors" produced images

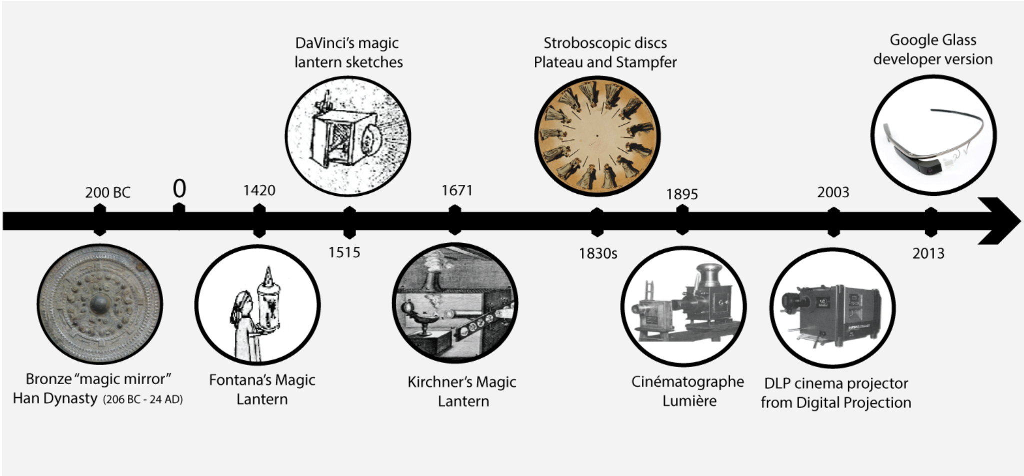

Figure 2.1: *Projection milestones in the last 2000 years (from left to right): bronze Chinese mirrors that projected patterns invisible with the naked eye; magic lantenrns, the first cinema projector and the first digital DLP cinema projector, and Google Glass that presents projected information in prism*

by reflecting light onto a screen without having any apparently visible patterns on the polished bronze plates that acted as mirrors [AP78; MY01]. The shadow theatre play originating from Asia is another early form of projection where flat figures are held between a light source and a transparent screen for the purpose of storytelling and entertainment [Lu+11; HB14]. The magic lanterns from the 17th century focused light from a candle or oil lamp projecting it through a painted slide onto a screen [Wil11]. Projection extended to moving images and early forms of cinema evolving from stroboscopic disks [Pri10] to Cinématographe Lumière, and then to digital projection through the invention of digital micromirror devices in 1991 [Hor91] (DLP projectors) that lowered the cost of projectors and made them widely available. With the availability of low-cost projectors, the HCI community implemented innovative applications and concepts using projection. Consequently, Tangible User Interfaces were introduced with the works of Fitzmaurice et. al [FIB95], and Ishii and Ulmer [IU97] that proposed to seamlessly couple of physical objects with digital information.

More recently, in 2011, Rukzio et. al identified concepts, interaction techniques, and applications for personal projectors for pervasive computing [RHG11]. In the following year, Rukzio et. al identified the challenges in improving projection characteristics, such as resolution, luminosity, support for different surfaces, successful business domains, and from the HCI perspective, good interaction techniques, context-aware interfaces, and low-latency tracking algorithms [Ruk+12], and Huber et al. [Hub+12] categorized applications and interaction concepts for pico projectors into four groups, based on whether both projector and the projection surface were fixed or mobile. Two years later, Huber presented a research overview of "mobile projected user interfaces" [Hub14b], and Dachselt et al. [Dac+12] covered technical issues and novel applications, and speculated

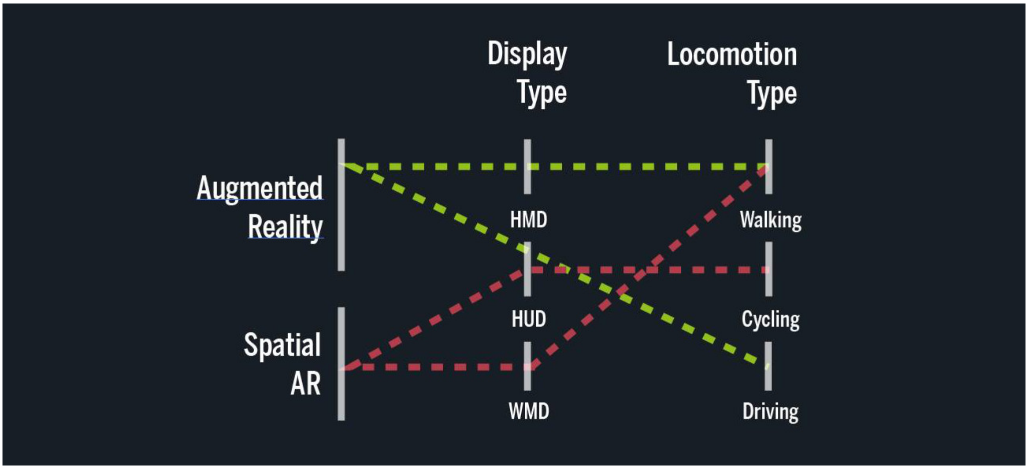

Figure 2.2: *Selected related research areas that are covered below (green lines) and own work (red lines) visualized using parallel coordinates. Abbreviations stand for Head-Mounted Displays (HMD), Head-Up Displays (HUD), Wearable Mid-air Display (WMD)*

about future social impacts, a time when projectors would be attachable, wearable, and embedded, creating experiences in a fused physical-digital space. Lochtefeld provides an overview on the types of projected displays in his PhD thesis [Loc14a].

The following sections will cover applications and devices that were researched and developed using projectors.

2.2.1 See-through projected displays

See-through projected displays have a long history. They were researched as part of avionic user interfaces, but also as wearable head-mounted displays. Recently both of this type of projected interfaces have become consumer products with their availability in the automotive industry and as smart glasses. Related research areas and the connection to own work are visualized in Figure 2.2.

Head-Up Displays

Head-Up Displays (HUD) have been researched in airplane cockpits [BF95; Fed06], but have recently benn introduced by many car manufacturers such as Audi, BMW, and Mercedes which developed a head-up display [Mer14]. showing speed, navigation, and lane guidance information, "keeping the eyes where they should be, focused on the road ahead". Consumer HUDs for cars have been released by Garmin [Gar] that project directly onto the windshield information about navigation, speed, and traffic. Jaguar has revealed a virtual windscreen concept that shows virtual cones for driver training, virtual cars for racing, and virtual racing lines for optimum track route and braking [Jag14]. As HUDs gain wider adoption in related industries, various aspects of their performance, safety and applicability should be evaluated. Research on aviation interfaces has shown that important information should be displayed closer to the "normal line of sight (NLOS), which is a line about 20° below the horizon extending from the eyes" [Wic13]. Human Machine Interface principles recommend having visual displays for in-vehicle interfaces positioned "as close as practicable to the driver's normal line of sight" and the driver should be able to assimilate relevant information with a few glances [Eur06].

Head-Mounted Displays

HMDs have been employed to augment the FOV of the user with information. Early implementations of wearable computers for augmented reality were the head-mounted displays of MIT [Sta+97] and Feiner et. al who prototyped mobile augmented reality systems for exploring urban environments using GPS-based navigation [Fei+97] (Figure 2.3, top).

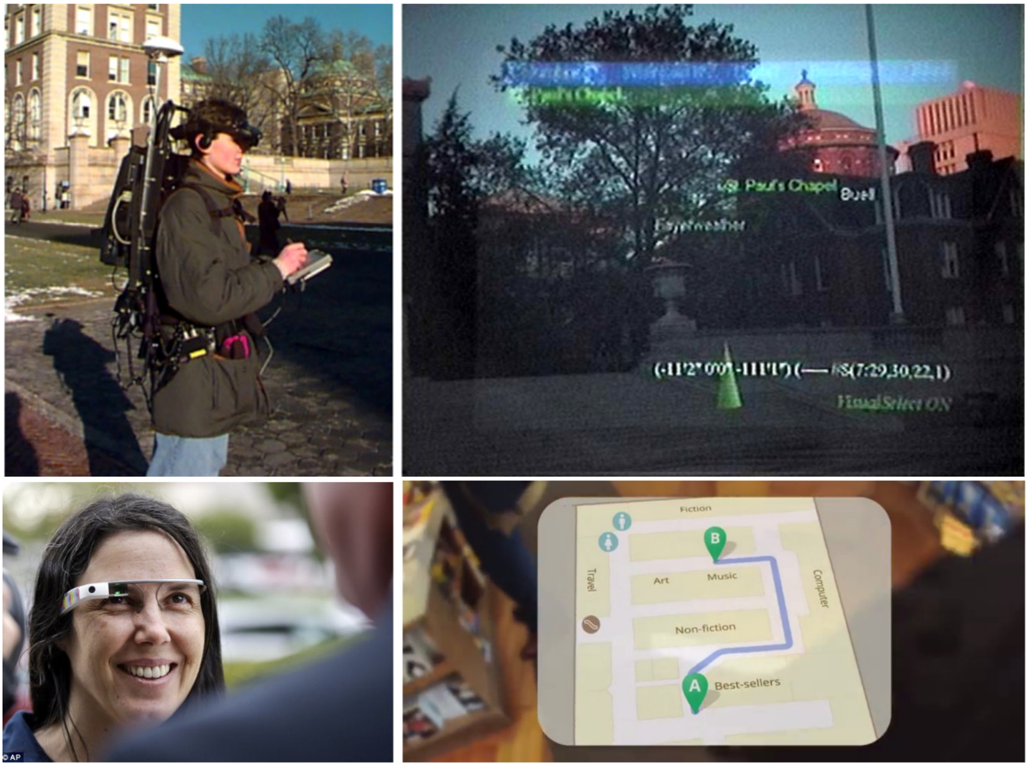

Figure 2.3: *The head-mounted display with augmented reality navigation application developed by Feiner et. al in 1997 [Ros+12] (top); Person wearing Google Glass [MP14] and map visualization from the concept video [Goo12] (bottom)*

Kress and Starner review a number of HMD technologies and applications that have become widely available due to the lower cost [KS13]. A comparison with technical specifications between commercial HMDs was maintained by Bungert [Bun16]. Smart glasses have recently attracted the attention of HCI researchers and industry with the lightweight commercial eyewear made available by Google [Goo12] and the more advanced HoloLens []. Figure 2.3 shows a comparison between Feiner's 1997 head-mounted display and smartglasses from 2014. We did not consider the recent generation of head-mounted displays such as Google Glass [Goo12] or Microsoft HoloLens [Mic16] since they may be perceived as obtrusive and do not support direct interaction. Similarly, we disregarded the new crop of smart watches because of their small displays which require users to split their attention between the display and the surrounding world.

In our experiments from papers E, F, G, projection augments the physical environment in front of the user who walks or cycles. The area of the environment that displays the contextual information is in the direction of locomotion inside the field of view. In the interfaces used for cycling (Smart Flashlight and Gesture Bike) the projection has a double role, acting both as a flashlight during the night and displaying the map used for navigation. In the wearable display protototype (paper H), our approach was informed by an online survey we carried out to gain information on user preferences. Based on our survey results, we created a wearable mid-air display prototype with two alternative body mounts. Based on a pilot study, we improved the prototype and used it within an experiment.

2.2.2 Projection on Body

Projection directly into the eye of the user has been experimented with in early user interfaces for pilots [Fur86] that were developed further into the Virtual Retina Display [Tid+95], and are currenlty being explored by companies such as Microvision [Lew04], Brother [Ric10], and Magic Leap [MIT15; Ron15].

Interaction with on-skin projected interfaces has emerged after PALMbit [YS07] and Skinput [HTM10] led to this new research direction. Harrison et al. [HBW11] implemented and evaluated a shoulder-mounted depth sensor-projector system that enables multi-touch interaction on the body and on arbitrary surfaces. In contrast, our work (paper H) projects images in mid-air relative to the user's body. The advantage is that the image can be displayed anywhere in the field of view but still be controlled directly or indirectly by our body.

2.2.3 Projection onto the Environment

We categorize the projection onto the environment section from the projector placement and mobility perspective. Hence the following subsections will be covered: fixed projectors, self-actuated projectors, handheld projectors, and wearable projectors.

Fixed projectors

Raskar et. al proposed to use digital light projectors to render images and virtual objects directly onto the physical space of the user without having the need to wear head-mounted displays [RWF98]. The concept was similar to the *everywhere displays* provided as a service by public infrastructure, where projectors could be used for displaying graphical interactive displays as opposed to users carrying devices [Pin01].

Fitzmaurice suggested that electronic information should be associated with physical objects in the physical environment [Fit93]. Tangible User Interfaces can be traced back to the collaboration of Fitzmaurice, Ishii and Buxton, proposing that virtual objects could be directly controlled through physical handles [FIB95]. At the same time, Fjeld et. al [FBR97] developed a projection system as part of an architectural design room where bricks were used for direct manipulation of information and argued as being a natural user interface that extends the concept of augmented reality.

Projection has been used to develop tangible interfaces, distributing computation across a range of devices, augmenting everyday objects with computational power (e.g. pens, paper, cups, toys), and creating interactive environments [Dou04]. These concepts are still operative today and appreciated the HCI community. For example, Jones et. al developed a proof-of-concept [Jon+13] projecting images around the television screen in order to enhance gaming experiences. The concept evolved into a projection system that transforms any room into an immersive experience where the user is able to touch, shoot, and steer projected content [Jon+14].

Self-actuated projectors

The Displaydrone is a multicopter equipped with a video projector connected to a mobile phone that projects images onto walls and objects in the physical space, enabling exploration of social group interactions in outdoor public spaces [Sch+13]. A floating interface displaying an avatar was created by Tobita et. al using a helium-inflated blimp carrying a small computer connected to speakers, and a projector displaying images on the surface of the blimp [TMK11]. The Autonomous Wandering Interface concept, consists of a quadcopter-projector system that follows a user walking outdoors projecting an interface on the ground around the feet [Luk14]. Keeker is a mobile terrestrial robot equipped with two motorized wheels, a projector, and surround sound controlled through the mobile phone providing applications for entertainment, chatting, and home monitoring [Kee14].

Handheld projectors

Willis provides an overview on handheld projector-based interaction [Wil11]. Cauchard et al. [Cau+12] identify challenges of handheld pico-projectors used on walls, desks, and floors, suggesting that this setting is unsuitable for many tasks. MotionBeam is a mobile projector that couples the movement of the projection to the imagery [WPS11]. ProjectorKit provides technical support for rapid prototyping of mobile projector interaction techniques [Wei+13]. Molyneaux et al. [Mol+12] developed a handheld projector aware of geometry, displaying content accordingly and enabling multi-touch interaction on arbitrary surfaces.

Wearable projectors

Wear-Ur-World is a wearable gestural information interface using a head-worn projector and arbitrary surfaces [MMC09]. Interaction techniques have also been prototyped with simulated wrist-worn projectors and wall surfaces [BCF05]. Ota et al. [Ota+10] explored 16 body locations for wearing multiple projectors for navigation and a photo-slide show while walking and standing, displaying information on floors. The *ambient mobile pervasive display* is a shoulder-mounted projector able to display on surfaces around the environment, the floor, and the hand [Win+14].

The growing use of mobile projectors reveals a need for better understanding of how to design interaction with such devices. Paper E presents design considerations on designing mobile projection applications and papers F and G propose the context of cycling as a design space for projector applications.

2.3 Map Navigation

The concepts and prototypes from papers E – H were implemented using projection and they present information relative to the human body for the task of map navigation. However, the design of digital maps and the study of wayfinding behavior [Gol99] was not the main topic of research. Wayfinding and following a simple route on a digital map was only the task used to evaluate the novel concepts and interfaces.

The widespread use of GPS navigation on smartphones and the development of novel location-based services and applications have influenced people's day-to-day activities and relationship to their environment. Location-based services have changed the way we eat [Yel], take a taxi [Ube], and avoid traffic [Waz]. A large-scale analysis of smartphone applications and corresponding contexts of use has shown that maps are most often used during free-time, checking restaurants, and during holidays [DBG11]. Baus et. al present a survey of mobile guides that make use of maps or map-like representations suggesting the need for future improvements in terms of how the maps are used and displayed on mobile devices [BCK05].

Digital map design was influenced by the ubiquitous computing paradigm [Sch09]. People use computational devices in everyday activities such as as walking, cycling, and driving. In the following subsections, we will review related work on map navigation during walking, cycling, and driving context of use.

2.3.1 Walking

Several factors influence the performance of pedestrian navigation interfaces, such as display size and landmarks which we will discuss below together with relevant results from our own work.

Gartner and Hiller [GH09] assessed in their pedestrian navigation field test the impact of restricted *display size* on spatial knowledge acquisition by comparing a mobile device ($25.8cm^2$) with a paper map ($222.7cm^2$). They found that in the case of the smaller display of the mobile device (that required panning), the sense of direction and spatial knowledge were outperformed by the paper map. In the evaluation of our Smart Flashlight prototype (paper F) the display sizes compared were $80cm^2$ for the smartphone and $7200cm^2$ for the projection. Although in our experiment the display was placed at different distances from the eyes of the user (handlebars and road projection) and the context of use was cycling during the night, most of the subjects appreciated the large projector display because it increased the map's clarity. In contrast, some reported missing turns with the phone display, as it was easy to forget about the small device. The safety concerns of looking down into a small mobile screen caused some stress, whereas looking at the projection was much less distracting, allowing peripheral vision to remain on the road. But this was not universal: some subjects preferred the mobile instead, as they could keep the map in memory and focus fully on traffic, with one writing how the greater effort to glance at the mobile encouraged better memory.

A requirements study for pedestrian navigation aids showed that *landmarks* were the preferred navigation cue, that street names were rarely used, and that map information is used to enhance pedestrian's confidence and support navigation decision [May+03]. In Gesture Bike (paper G), we added landmarks on our routes in order to aid route navigation.

Navigation in an urban environment was the application scenario of an early augmented reality head-mounted display developed by Feiner et. al [Fei+97]. More recently, Huang et. al compared an AR interface, a map-based interface, and a voice interface for pedestrian navigation showing that the AR interface was slightly better in landmark recognition and route direction, but the differences were not significant [HSG12]. These results would be interesting to test in the context of cycling – on the HMD of Gesture Bike or on the wearable mid-air display prototype presented in paper H.

2.3.2 Cycling

Bicycles are a sustainable and efficient locomotion solution since a man on bicycle "ranks first in efficiency among traveling animals and machines in terms of energy consumed in moving a certain distance as a function of body weight" [Wil73]. Developing visual

Figure 2.4: *Map navigation interface displayed on tablet mounted under handlebars. Copenhagen City Bike,* `bycyklen.dk`

interfaces for bicycles might be important since in the last 10 years there were over 1 billion bicycles produced [Ron08].

Map navigation is a popular application on mobile phones that is also used while cycling. Alternative technologies have been developed for this purpose and research has been conducted exploring this context. Exploratory bike trips using handlebar-mounted smartphones offered map navigation while cycling [Pie+12b]. It was reported that by not offering turn-by-turn navigation, the bike rider could be more aware of the environment, but most cyclists had to stop to read the map anyway, "since they found it too small" [Pie+12b]. The bike-sharing system in Copenhagen equipped its bicycle fleet with touch screens mounted below the handlebar (Figure 2.4), offering GPS map navigation and real-time departure times of trains, buses and the metro [Byc14].

Previous work by Rowland et al. on designing interactive experiences for cyclists employed mobile phones mounted on the bicycle's handlebars or worn on the cyclist's lower arm [Row+09]. Audio instructions were employed to support a "heads-up approach", however one user was very distracted and in danger of a collision. They found that for map navigation, adapting digital media to the cycling activity was essential. Hammerhead is a T-shaped handlebar-mounted device connected to the smartphone, helping with turn-by-turn bike navigation using LED lights [MWB14]. Another way to improve the safety while cycling is considering the routes and informing cyclists about their characteristics [Red+10].

2.3.3 Driving

GPS map navigation is considered a skilled activity where users should support their navigation with the system and not follow instructions blindly [BL12a]. Design choices are drawn from recent GPS navigation guidelines suggesting active drivers are "interpreting, ignoring, and re-using instructions while also combining them with related information from the environment and their own route knowledge" [BL12a].

Automotive experts consider that map data is required in order to support accurate localization and to enable decision making [Ber15b]. Advantages of using digital maps while driving include [Ber15b]: to provide long range planning, preview beyond sensor range allows early adaptation to road conditions, and lack of preview in dense traffic might lead to emergency stopping at lane end. Three map types are distinguished [Ber15b]: 1) planning map "Your lane ends at GPS position x y"; 2) localization map "You are currently at GPS position x y"; 3) decision algorithm "Merge right within the next 150 meters" [Ber15b]. For the evaluation of our prototypes, we employed a localization map (papers E – H).

Important information inside moving vehicles should be displayed closer to the "normal line of sight (NLOS), which is a line about 20° below the horizon extending from the eyes" [Wic13]. Human Machine Interface principles recommend having visual displays for in-vehicle interfaces positioned "as close as practicable to the driver's normal line of sight" and the driver should be able to assimilate relevant information with a few glances [Eur06]. Head-up-displays have been researched in cockpits and have recently been introduced by many car manufacturers showing speed, navigation, and lane guidance information, "keeping the eyes where they should be, focused on the road ahead" [Mer14].

Figure 2.5: *Concept car communicates with pedestrians [Nis15]. Courtesy of Nissan.*

Consumer HUDs for cars have been released by Garmin [Gar] that project directly onto the windshield information about navigation, speed, and traffic. Jaguar revealed a virtual windscreen concept that shows virtual cones for driver training, virtual cars for racing, and virtual racing lines for optimum track route and braking [Jag14]. As HUDs gain wider adoption in related industries, various aspects of their performance, safety and applicability should be evaluated. Human Machine Interface principles for in-vehicle interfaces suggest that the driver should be able to assimilate relevant information with a few glances, system dialogues should allow the assessment of information priority, and information with higher safety relevance should be given higher priority [Bek08].

Since autonomous vehicles will be widely available by 2025 [Ber15a], with companies such as Tesla demonstrating this function already [McH15], automotive visual interfaces will look different in the future. Communicating with pedestrians and participants in traffic will become important issues since the human driver will disappear. One example is Nissan's concept car showcased in 2015 [Nis15] introducing a system called *Intention Indicator* that communicates with pedestrians (Figure 2.5). Paper F and G propose replacing headlights with projectors and augmenting the space around vehicles with information. Our proof-of-concept experiments employed bicycle-mounted projectors.

2.3.4 Urban Mobility

There is a need for research into mobile technologies for situations where people move as the activity occurs and it has been argued that the movement itself can be a topic of investigation [Wei03]. Physical movement of persons and artifacts is distinguished from *mobility* which focuses on the "social dimensions associated with movement and use of mobile technology" [Wei03]. The role of locomotion in HCI has seen an increase due to

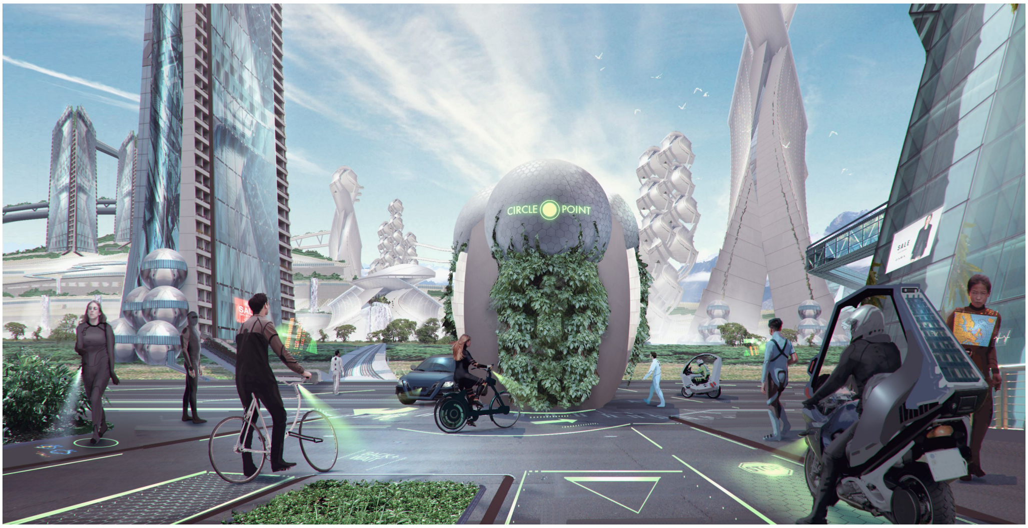

Figure 2.6: *Vision of projected interfaces in an urban environment. Concept by author, illustrated by Simon Fetscher.*

popular applications used in mobile contexts. Map navigation and sports applications are two examples where locomotion is essential and are now commonly used on mobile phones. This trend will continue and new urban mobility solutions appear based on corresponding human needs. Based on advancement of projector technology through decrease in illumination cost, increase in brightness [Fis06], and on market predictions [Res16], we envision a future where projectors could replace vehicle headlights and enable body-centric projected interfaces for use during locomotion in urban environments, as shown in the illustration below.

The world's population living in cities is increasing, from 53% currently living in urban areas to 67% by 2050. In 2013, 64% of all kilometers travelled were within urban environments and "the total amount of urban kilometers travelled is expected to triple by 2050" [Art13]. As the urban mobility demand increases, mobility needs evolve through fast, convenient services that offer flexible solutions in urban transportation [Art13]. Cities such as London and Berlin have implemented progressive policies through major investments in public transport, walking, and cycling services [LSE15]. Cities such as New York, London, Paris, and Singapore have already closed parts of their city centers to motorized traffic introducing pedestrian zones, while 850 cities had introduced bike sharing programs by 2015 [Bou+15].

New transportation technologies are being developed, and a wide range of battery-powered locomotion devices has already come to market, such as electric skateboards, unicycles, self balancing scooters and dual wheels. These new devices could use projection to signal movement-specific visualizations such as direction and speed, thus improving safety and displaying relevant contextual information.

2.4 Body-Centric HCI

As interaction with digital information becomes our second nature, HCI researchers are developing interfaces as our second skin. Using the skin of the human body as an input device was argued by Harrison et. al through the large surface area available and proprioception, the sense of knowing the location of body parts without looking [HTM10]. Consequently, they developed a wearable bio-acoustic sensing array as an armband that was able to sense finger taps on the arm and hand. As output, they used pico projectors to display tappable buttons on the skin. Based on recent developments in electronic skin and organic electronics, Weigel et. al developed a flexible, stretchable, thin skin-worn sensor for single and multitouch input. Steimle considers that *embodied interfaces* “take advantage of our physical skills: we are good at expressive physical interactions, fine motor movements, and have a strong sense for spatial location and arrangements” [Ste15].

Body-centric models for human-computer interaction have been developed in the past through morphological analysis of the design space of input devices [CMR91]. Card et. al proposed a taxonomy of input devices and described parametrically the design space by taking into account parameters such as bandwidth of muscle group, task precision, device bandwidth, and device precision. More recently, more HCI body-centric models have been proposed for interaction with large displays, and multi-surface environments, using sensors for tracking the human body [Wag+13; Che+12; Sho+10]. Wagner et. al distinguish two physical dimensions: user input and visual output that can be relative to the body and fixed in the world. Based on these dimensions they propose a body-centric approach to describe and compare multi-surface interaction techniques [Wag+13]. They draw on kinesiology and neurobiology research that describes how people perform complex motor skills, “adjusting their bodies during coordinated movements, based on constraints in the physical environment or the bodys own kinematic structure” [Mas92; Wag+13]. Shoemaker et. al formultate body-centric interaction techniques guidelines for large displays that unify interaction spaces: design representations that bind personal and extrapersonal space should mediate interaction at a distance; employing proprioreception allows operations in personal space without visual feedback; private space must be considered and employed; bodily cues such as posture to manage coordination. These guidelines are drawn from research on Reality-Based Interaction [Jac+08] that emphasizes body awareness and skills, five themes for Interaction Design: *thinking through doing, performance, visibility, risk, thick practice*, and neuropsychology research that distinguishes between representations of space that the brain builds: *personal space* (occupied by body), peripersonal space (within reach), and *extrapersonal space* (outside reach) [HS04]. Inspired by these proximal spaces of the human body, Chen et. al developed body-centric interaction with mobile devices that employ the on-body space and around-body space [Che+12]. Extending motor space through transformation and movement of the interface around the bounded visual space is a more recent approach to deal with physical constraints of displays [TSK15].

2.4.1 Wearables

Wearable Computing has been defined in many ways over the last decades. Rhodes notes that a wearable computer should be comfortable, easy to keep and use, as unobtrusive as clothing, and possessing the following characteristics: operational while walking or moving, hands-free use (e.g. speech input and heads-up display or speech output), sense context of the physical environment, proactive (communicate information even when not used actively), always on [Rho97].

The definition of Kortuem et. al builds on the previous, expanding it with a user interface that "presents information in an unobtrusive, context-dependent manner" [KSB98]. Mann defines wearable computing as "the study or practice of inventing, designing, building, or using miniature body-borne computational and sensory devices. Wearable computers may be worn under, over, or in clothing, or may also be themselves clothes" [SD15]. Starner adds that the wearable computer should observe the physical and mental state of the user, should manage potential interruptions like phone calls or e-mail, filter them based on the user needs and preferences, and adapt its input and output modalities to the "most appropriate and socially graceful at the time". Gemperle et al. defined the concept of *wearability* "as the interaction between the human body and the wearable object'. Dynamic wearability extends that definition to include the human body in motion" [Gem+98]. They created guidelines about placement, shape, human movement, perception of space, diversity of human body, attachments to body, weight, accessibility, sensors, thermal, aesthetics, and long term use.

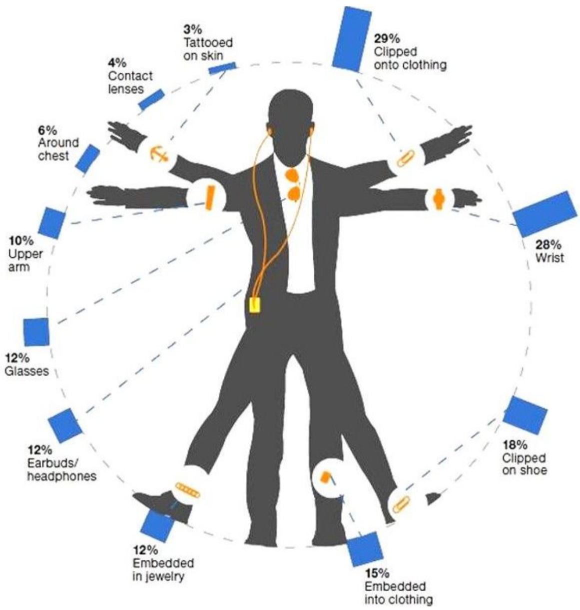

Figure 2.7: *Online survey results asking "How would you be interested in wearing a sensor device?" [Res14]*

Prototypes of smartwatches and smartglasses were developed in the past in research labs and are only now hitting the market. Commercial wearable sensors without displays became popular as activity trackers. Smartwatches and smartglasses easily integrated such functions. Although these two wearable displays are worn only on two body parts, it is worth looking at the potential adoption of society regarding the preferred location of a wearable sensor device. Figure 2.7 depicts the results of an online survey carried out in 2013 in the USA with 4,656 adults [Res14]. Paper H asked similar questions regarding a wearable display that would display floating images in mid-air relative to the body of the user. An interesting agreement of both studies is the high rating of clipping devices onto clothing that contrasts with the lack of this design solution of interactive devices on the current market.

2.4.2 Space of Interaction

The features of space identified by Harisson and Dourish [HD96] as a model for collaboration are the following: relational orientation and reciprocity (spatial organization of the world and our understanding of it in our field-of-view), proximity and action (understanding proximity and interaction with close objects and people through movement and language), partitioning (space can be partitioned since actions "fall off with distance"), presence and awareness ("as we move around the everyday world", we sense the presence of people, their actions, and the corresponding representations of their activities).

Edward Hall's *proxemics* theory described how space is used depending on different measured distances from a person: intimate (<0.5m, close relationships), personal (<1.2m, interacting with friends and family), social (<3.5m, formal settings), public (>3.5m, addressing others as a speaker) [Hal66]. Several proxemic theories have been used in HCI research to analyze interactions with interactive technologies [VB04; MRP11; MG15]. Marquardt and Greenberg proposed *proxemic dimensions* that apply to "entities" such as people, devices, and objects: distance (measurable length between entities), orientation (e.g. gaze for people or front-facing side of a display), movement and motion (absolute or relative changes in position of entities), identity (unique information about an entity), location ("qualitative and quantitative aspects of the place where the interaction takes place") [MG15].

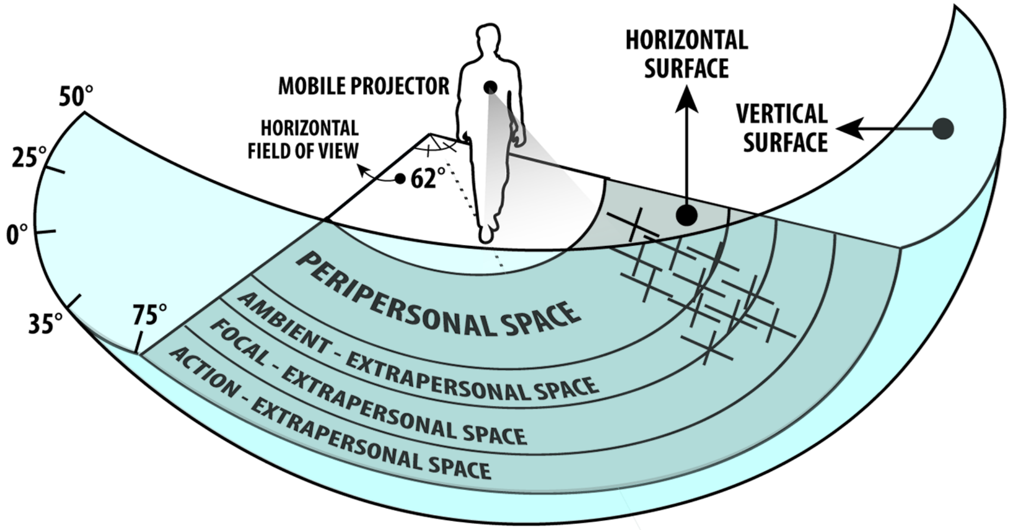

Figure 2.8: *Action spaces (ambient, focal, action), based on [CD07b]*

Neuropsychology research that distinguishes between representations of space that the brain builds: *personal space* (occupied by body), peripersonal space (within reach), and *extrapersonal space* (outside reach) [HS04]. Humans have evolved to use peripersonal space for reaching and manipulation and action-extrapersonal space for navigation [CD07b].

In paper E, we explored these action spaces for display of information using projectors.

Peripersonal space could be used to display private information, while extrapersonal spaces could be employed to display information regarding navigation (Figure 2.8). This extends human reach into the collocated space and illustrates our new ability to modify it instantly. Extending motor space through transformation and movement of the interface around the bounded visual space is a more recent approach to deal with physical constraints of displays [TSK15].

2.4.3 Natural User Interfaces

Natural User Interfaces (NUI) enable users to interact with computers "in the same ways they interact with the physical world, through using their voices, hands, and bodies" [PSR15]. These interfaces have been supported by the availability and popularity of sensors from gaming consoles such as Wii and Kinect that create an interaction space in front of the television engaging the whole body of the user.

In our work, we proposed that contextual information can be displayed where it is needed, and interaction can harness already known tasks and expectations. Two examples are Smart Flashlight (paper F) that replaces the headlight of the bicycle with information and Gesture Bike (paper G) that detects the gestures employed by cyclists in traffic making them more visible by projecting corresponding signals on the road in the vicinity of the bike. These interfaces used in dynamic contexts make use of already known tasks and expectations, augmenting the action and activity of the user.

3 Methodology

Our research sought to evaluate our prototypes in dynamic and complex real-life contexts. This approach was adopted in order "to ensure that human values and human priorities are advanced and not diminished through new technology. This is what created HCI; it is what led HCI onto and then off the desktop; it will continue to lead HCI to new regions of technology-mediated human possibility" [CR13; Cra+13].

3.1 Human-Centered Design

This thesis follows User-Centered Design methodologies for our experimental contributions [PSR15; MS07]. Moggridge sees Interaction Design at the intersection between the design disciplines, human sciences, engineering disciplines, and technical sciences, as a "discipline that can create solutions with human and subjective qualities in a digital context". The purpose is to make "technology fit easily into people's everyday lives, rather than forcing their lives to fit the dictates of technology" [MS07].

The research methods from our field experiments for evaluating the prototype were based on collecting qualitative data based on questionnaires (e.g. NASA TLX, SUS, MARS) that assessed task load, system usability, situation awareness, ease of use and perceived safety of the system. Often interviews were also performed after the completion of the questionnaires. Field experiments are defined as quantitative experimental evaluations that draw on both aspects of qualitative field studies and lab experiments [GBG04]. Online surveys based on video prototyping informed our design choices. Early evaluation of the prototypes, pilot studies often improved the design significantly. Since the prototypes in the second part of the thesis explored different placements of the visual interfaces for the task of map navigation, it was considered important to run the evaluation in real-life conditions, on the streets of urban environments. Moreover, two prototypes, Smart Flashlight and Gesture Bike, involved road projections around the bicycle and real traffic situations were encountered by participants. These evaluations are necessary when designing interfaces used in motion.

Terry Winograd noted that we interact with the physical world through the following main actions [MS07]:

- manipulation – "move things around with your hands"
- locomotion – "move yourself from place to place"
- conversation – "you say something and another person says something back"

While all these everyday actions have been used as metaphors in early graphical user interfaces for interaction with personal computers, they have been implemented in our everyday lives and are augmenting our actions (e.g. manipulation – tangible interfaces). Of particular interest in this thesis is locomotion which is performed through actions such as walking and cycling. Since mobile interactive devices are always in our pockets during these activities, designing for this main way we interact with the world so as not to impede this activity, but to support it, becomes critical in human-centered design.

3.1.1 Complexity of the digital world

Don Norman notes in *Living with Complexity* [Nor10] that "the whole point of human-centered design is to tame complexity, to turn what would appear to be a complicated tool into one that fits the task, one that is understandable, usable, enjoyable" [Nor10]. Tesler's Law of the Conservation of Complexity says that the total amount of complexity in a computing system is constant; making things easier for the user increases the complexity in designing the system for the engineer or designer [Saf06; Nor10].

We have tacit assumptions of using these technologies that complicate our lives, such as carrying and holding a mobile phone in one hand or sitting down when using a computer, and since these devices are so widely used, people perform these actions without thinking about them; they became second nature. How should we design technology and on which assumptions should it be based? If we remove technological limitations and complexity, what are the first principles that should guide us in designing for the mobile human?

3.1.2 From the lab into "the wild"

There has been a paradigm shift in human-computer interaction – researchers are leaving the "safety and security of their controlled, lab-based environments and moving their research out into the wild " [Cha+12]. More HCI studies are carried out with people in their home environments and on the street. Designing interactive systems based only on laboratory studies without longer term user involvement does not provide sufficient insights into these technologies [Cha+12].

A 2003 review of Kjeldskov and Graham showed 71% of all evaluation of mobile devices and services was performed in the lab [KG03]. Only six years later, in 2009, lab experiments accounted for 49%, while the second most used method was field studies accounting for 35% of the mobile HCI research methods [KP12], while in 2014 it is not a question of *if*, but rather of *when* and *how* field evaluation should take place [KS14].

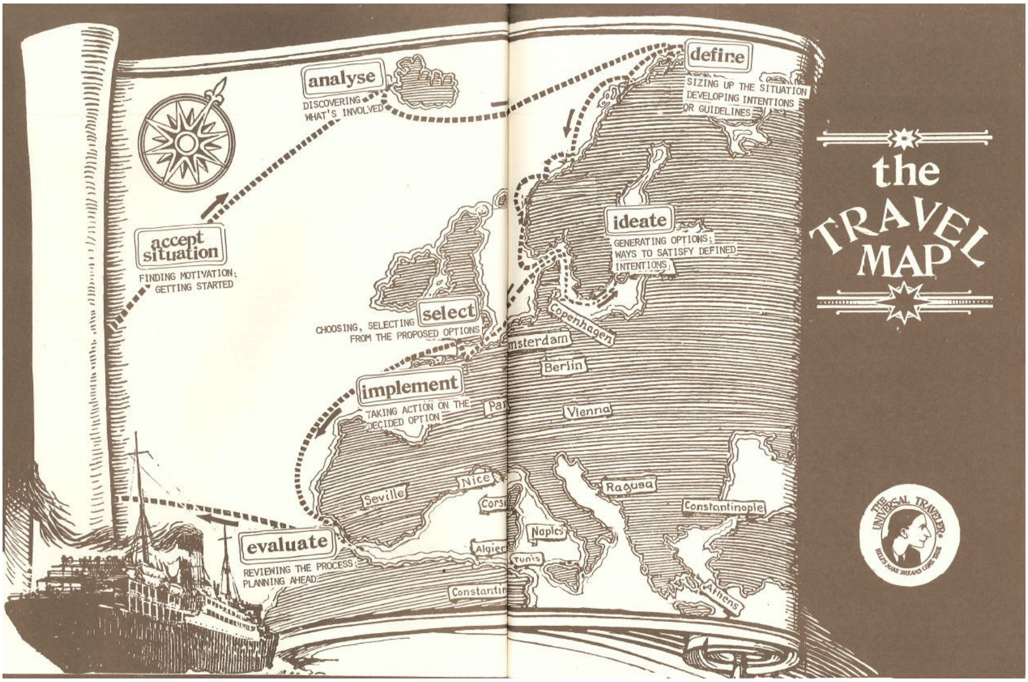

Figure 3.1: *Stages in the process of design according to Koberg and Bagnall [KB76]*

3.2 Design Approach

The process of design is a creative problem-solving journey that goes through the stages of accepting the problem, analyzing, defining goals, ideating, selecting, implementing, and evaluating that are beautifully illustrated by Koberg and Bagnall in Figure 3.1. Similar stages of design are taught at universities under the name of *Design Thinking* [dsc16].

3.2.1 Ideation

This is considered an essential stage in the design process. Table 3.1 depicts the timeline for a CHI/UIST paper, but does not show the time required for developing “The Hunch”.

Depending on one's interest, passion, and goals, this time varies greatly. This section documents some of the methods employed for this stage of development.

Creativity and Innovation

James Adams writes in his *Guide to Better Ideas* [Ada74] about creativity and problem solving, focusing on emotional and intellectual aspects of design. Several obstacles or blocks hinder the perception and information needed to solve the problem, such as perceptual, cultural and environmental, emotional, intellectual and expressive blocks. Some examples of these include delimiting the problem area too closely, inability to see the problem from various viewpoints, taboos, humor, intuition, supportive environments, fear of taking risks [Ada74].

Many of these topics are valued today in academia and innovative organizations. Scholars and consultants agree that the following conditions contribute to innovation [BBB12]: a common goal of the research group; shared *values* that support innovation; an environment where it is safe to try out, pilot, test, and experiment ideas; provision of the *tools*, training, and techniques to innovate; promotion of *diversity* and injection of new ideas by inviting speakers, experts for talks, visiting professors, students with different backgrounds; supporting *interaction* through events and forums as an opportunity to exchange ideas and build networks, and providing *time-out* through access to slack resources.

Brainstorming

The Brainstorming technique was coined in 1942 by Alex Osborn, the founder of an advertising agency, who published several books on the topic of *creative thinking* [Osb42]. Since its inception, this method has been employed in a range of fields and has been addressed by many authors with different backgrounds such as architecture, design, arts, and engineering. A compendium of idea generation methods has been put together by Leith [Lei05; Loc14b]

Seven ideation techniques of innovation consultant Bryan Mattimore are the following: questioning assumptions, opportunity redefinition (replacing words randomly as a trigger for discussion), wishing (asking what if), triggered brainwalking (circulating a sheet of paper containing one topic on which everybody writes their ideas), semantic intuition (making three word categories related to the challenge, varying words and combining words in different categories), picture prompts (using as triggers interesting images with varied subject matter, different types of interactions, and relationships to people), worst idea (creating list with terrible ideas that get ideation participants laughing and re-engaged, then turning these ideas into their opposites) [Mat12]. Among these, the most used ones were: questioning assumptions, asking what if, and picture prompts of early prototypes from pilot studies that helped with developing ideas further.

Lists

Attending conferences and participating in workshops early on was considered important since the Human-Computer Interaction community is sensitive to trends and different schools of thought (e.g. technology-driven vs. human-centered). Spontaneous conversations with researchers of different backgrounds can trigger new research directions, exchanging valuable related work, collaborations, and learning new research styles and methods.

For keeping focus, one can keep a journal of ideas and the development process. At all times, a list of ideas organized into two groups was maintained in these journals acting as an inspiration and discussion trigger. The first group contained selected projects from crowdfunding communities, such as `kickstarter.com` with inspirational videos that call for the community to support the ideas by pre-ordering before production and deployment begins. Crowdfunding platforms act as a filter for successful ideas, showing a population's culture, understanding, and current technological interest.

How these crowdfunding ideas were selected was based on personal interest and funding amount. Many projects are innovations and can act as inspiration for Interaction Design students. One example would be the Pebble smartwatch[1] backed in 2012 by 68 929 people on kickstarter, raising $10m. This project employed electronic paper to display the time and connected via Bluetooth to mobile phones. The product was delivered two years before Google's Android Wear platform was announced.

The second group of ideas was selected among the most attractive over time, by attending conferences, reviewing literature, and from ideation methods. It is worth mentioning that recording conversations and writing down ideas immediately after an initial discussion took place was helpful; first contact and initial exchange of ideas was usually the most enriching.

Another important approach was the combination of rest and intense work. Often many valuable ideas were obtained early during the day, during rest, travelling, or being in remote areas without a mobile phone, internet, familiar places or associations.

3.2.2 Filter

Finding and filtering ideas, developing concepts and evaluating them early was essential. International conferences filter the contribution and presentation of ideas; they guided us in establishing research directions and assured presentation standards.

Having done a comprehensive literature review, sketching and developing prototypes was not enough. Initially writing workshop papers and attending tutorials, workshops, and courses in HCI complement the above activities and skills and keeping at least two ideas and prototypes in parallel for a while, having early prototypes and early feedback, was a way of developing our design thinking and became an essential part of the design process. Many steps of the design process proceeded in parallel and may not follow a strict path. Some concepts may require more pilot studies until the prototype design and concept improve.

Many hardware and software prototypes were developed in order to explore research directions using prototypes that were necessary in order to be able to think about the design problem. Some of the prototypes included 3D printed pico projectors holders equipped with movable mirrors, small Linux computers (Pandaboard, Raspberry Pi, NVIDIA Jetson) connected to depth sensors processing depth information in real-time,

[1]Pebble smartwatch: `https://www.pebble.com`

testing the setup developed by 3Gear [Sys14] for tracking hands in an office environment using a pair of depth sensors mounted on an aluminum frame, software prototype on 3D map visualization (Cinder library), software prototype tracking the whole body developed with two graphics engines (OGRE and Irrlicht), mapping full body tracking to camera view movements in an Earth orbit rendering application (OpenGL) based on atmospheric scattering research [Nis+93], gesture recognition prototypes (OpenGL and OpenNI).

Developing prototypes, writing papers, and attending international conferences created an understanding and skills in identifying and materializing scientific contributions. The next section will present prototypes related to or from published papers on the mobile visual interface topic.

3.2.3 Prototyping

The technical prototyping approaches of the thesis are described in the Physical Computing manual of O'Sullivan and Igoe [OI04]. Although their approach is apparently technical, their goal is human-centered arguing that "we need computers that respond to the rest of your body and the rest of your world" and that "we need to think about computers that sense more of your body, serve you in more places, and convey physical expression in addition to information" [OI04].

Innovative designs are the result of the interplay between a list of specifications that represent novel concepts and the prototypes that aim to embody the new ideas [Win96]. David Kelley from the design firm IDEO suggested twenty years ago that innovative organizations are moving "from specification-driven prototypes to prototype-driven specifications" [Win96] (pp 195). For example, Honda and Motorola were building upto 12 prototypes with a new trial every 2 weeks. This type of prototyping culture can provide a measureable way of improving a product and tracking progress.

Besides prototyping with the open-source Arduino platform[2] which provides easy-to-use hardware and software, additional materials such as wood, plexiglass, styrofoam, metal, and tools such as CAD modeling in Blender, 3D printing, and pico projectors were employed in rapid prototyping. The range of materials and tools provided the means to ideate and experiment with input and output computing capabilities. Rapid prototyping and quick iteration of experiments contributed in improving the concepts and our skills. During the series of design processes, the methodologies were increasingly refined. These were combined with collaborations and experiences of many colleagues from different backgrounds who offered valuable critical views and feedback.

3.2.4 Evaluation

The context of use of environment- and body-centric projection was highly dynamic, the latter being outdoors during locomotion. In-the-wild evaluation of mobile interfaces is becoming more widespread since HCI researchers leave their "lab-based environments and move their research out *into the wild*" [Cha+12].

When discussing field evaluation of location-based services, Goodman et. al define field experimental evaluations that collect quantitative and qualitative measures such

[2] Arduino platform: `https://www.arduino.cc/`

as: task completion time, error rate, perceived workload, distance travelled, and "extent to which the use of a device disrupts normal walking" [GBG04]. The research methods for evaluation of our prototypes were based on field experiments collecting qualitative and quantitative data based on questionnaires that assessed task load, system usability, situation awareness, ease of use and perceived safety of the system.

According to Goodman et. al [GBG04] and Brush [Kru09] (pg 176), NASA Task Load Index (TLX) [HS88] is used in field experiments to measure task workload. It was used to evaluate the prototypes in paper F, G, and H. The System Usability Scale (SUS) and Mission Awareness Rating Scale (MARS) [MB02] were also used in papers G and H.

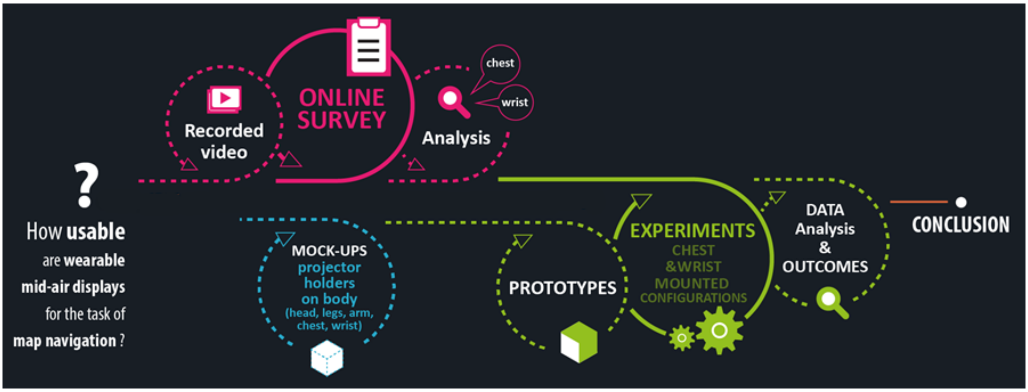

Figure 3.2: *Timeline for the methodology of the wearable mid-air display (paper H)*

Interviews were also performed after the completion of the questionnaires. Online surveys based on video prototyping informed our design choices. Figure shows the timeline describing the research on the wearable mid-air display. Early evaluation of the prototypes through pilot studies often improved the design significantly. Since the prototypes in the second part of the thesis explored different placements of the visual interfaces for the task of map navigation, it was considered important to run the evaluation in real-life condition, on the streets of urban environments. Moreover, two prototypes (Smart Flashlight and Gesture Bike) involved projected displays around the bicycle, so real traffic situations were encountered by participants. Such evaluations are necessary when designing interfaces used in motion.

3.3 Design Thinking

Although Engineering Design is normally seen as a technical process, it is actually a social process of negotiation and agreement between participants, each with their own background and "awareness of aspects of the object being designed" [Cro11; Buc94]. The specific knowledge in Interaction Design comes from the various disciplines depicted in Figure 3.4.

Nigel Cross identified in *Design Thinking* the following design strategies: i) having a "systems approach" to the problem; seeing relationships between entities, and not defining the problem in a narrow way ii) framing the problem in a unique, personal way iii) questioning assumptions and designing from "first principles".

Throughout the thesis, developing concepts and exploration were combined and guided by investigating the moving interface and designing for interaction in motion. The case of Gordon Murray illustrates that innovative design implies beginning to work with "first principles". The design ability is perceptual; it is a way of seeing [Cro11]. Similarly, Marcel Proust considers that "the real voyage of discovery consists not in seeking new landscapes, but in having new eyes". The initial problem formulation is a new perception of the design problem; to establish a new concept, it is almost as having to fabricate the problem [Cro11].

3.3.1 Exploratory Research

With these questions in mind, adopting a human-centered approach combined with physical computing methods, the following points have been probed and examined during the prototyping phase. Figure 3.3 illustrates the motivations for exploratory research: When the problem needs to be defined more precisely, to identify relevant courses of action, to develop hypotheses, to gain additional insights before an approach can be developed, establish priorities for further research, and isolate key variables and relationships for further research [Ste01].

Exploratory research distinguishes between *investigative exploration* (to study, examine, or investigate a phenomenon) and *innovative exploration* (where "testing or experimenting

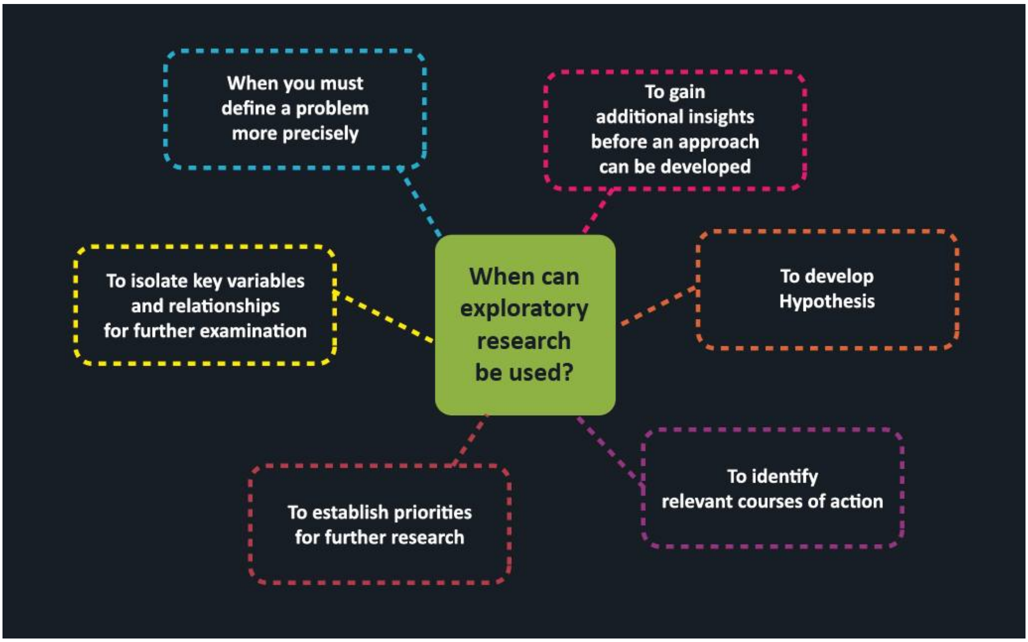

Figure 3.3: *Six arguments for when exploratory research can be used [Ste01]*

is done to create a particular effect or product") [Ste01]. Two examples of investigative explorations are paper E which attempts to project on the surface of snow and paper D which reports a phenomenon – the transmission of an infrared signal from a depth sensor through water and the possibility of reconstructing underwater surfaces using this technology. Innovative exploration encompasses all other articles that included more testing and evaluation.

Human-computer interaction is interdisciplinary by its nature. Exploring new materials and technologies, and focusing on their interaction has been argued as being relevant in identifying human needs [Sch15]. However, exploration in research methodology is rarely discussed. Often theoretical conclusions and premature methodological refinements end the process of exploration when it is still needed [Ste01].

New technologies such as "physical interaction, 3D printing, laser cutting, rapid fabrication, printing of circuits, displays and sensors, biomechanical modeling, and implanting electronics" are becoming widespread in the HCI community [Sch15]. Consequently, their exploration and human-centered re-invention have driven many contributions in the field. Innovating interactive devices requires both identifying gaps in interactive technologies, and becoming familiar with prototyping technologies and materials in order to combine them in novel ways, exploring different interfaces and interaction techniques.

3.3.2 Interdisciplinary collaboration

Interdisciplinary collaboration with the Department of Architecture, architect Stig Nielsen provided new tools, materials, and insights that led to publications on environment-centric projections (paper A, B). Collaboration with communication designer Adviye Ayça Ünlüer from Yıldız Technical University improved presentation and ideation techniques. These

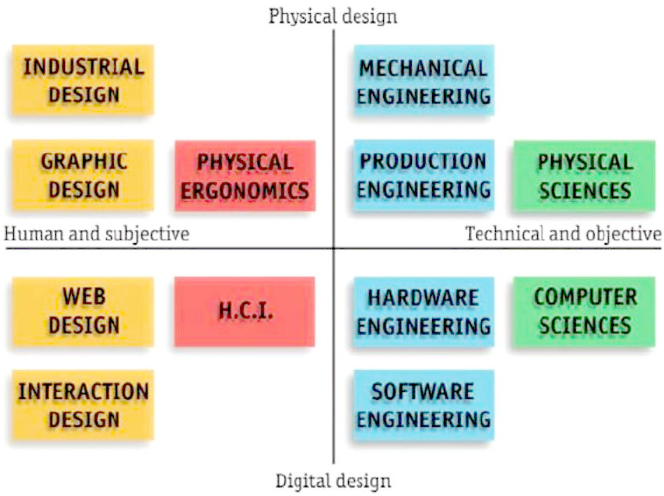

Figure 3.4: *The interdisciplinary field of Interaction Design according to Moggridge [MS07]. Courtesy of MIT Press.*

Timeline		
Start A	The Hunch	There's an idea, or a problem that fascinates you.
Start B	Research Question	Turn hunch into an academic question or start with RQ from thesis.
3 weeks	Literature Review	How was this addressed, how does the RQ change as a result?
1 week	Idea	How to add knowledge to the scientific community and answer RQ?
2 weeks	Exp. Design	What study is needed, if any, and what hypothesis would it answer?
1 week	System Design	What technology, if any, is needed for the experiment?
2 weeks	Paper Outline	Outline of paper with bullet points filled in (except for results).
x weeks	Implementation	Build it!
1-4 weeks	User Study	Run the evaluation.
1 week	Analysis	Experiment validated hypothesis? Any surprising findings? Explain.
2 weeks	Paper Draft	Fill in outline with what is known by now.
1 week	Circulate Draft	Get feedback from colleagues internally, then possibly externally.
1 week	Submission	Condense writing, integrate feedback, proofreading.
1 week	Video Submission	Storyboard, texts, scenes, video and still image materials.

Table 3.1: Timeline for a CHI/UIST paper, based on [Bau14]

methods were also employed during the Tangible Interaction course of the Interaction Design Masters programme at Chalmers University of Technology, for which I proposed and guided student projects for three consecutive years (2013, 2014, 2015).

3.3.3 Sprints

The methodologies from the thesis were organized in cycles or sprints inspired by the agile development principles [Bec+01] of self-organization and motivation, co-location, and that a working prototype is more important than a complete specification of the system that is normally established at the beginning of the prototype development cycle. Instead, several pilot studies were performed, and necessary changes were quickly implemented.

These sprints were limited by deadlines given by international ACM conferences in Human-Computer Interaction. Murray's case study from *Design Thinking* illustrates the importance that limited time and the corresponding pressure has on innovation: "In the midst of the pressure, the fervour, the panic, he used to get breakthroughs, [...] like suddenly a mental block's lifted" [Cro11]. Similarly, *Physical Computing* recommends: "Work fast and at a high level. Whenever possible use prefabricated technical solutions to at least test things. Don't spend your time perfecting endless details until you have proven the overall concept. The longer you spend implementing something, the more invested you will become in it and the less objective you become about its actual value to the project" [OI04].

Our organization of the design process was informed by the timeline for a CHI/UIST paper [Bau14]. However, these activities have never been sequential, but were intertwined and unique for every project. One good example is the wearable mid-air display prototype for which it was important to photograph (Figure 3.9) and record participants from their own perspective by wearing GoPro cameras, but also from street perspective. The videos helped us think about the problems; they were also used for the online survey whose results informed our experiment design, and at the last stage, they were also used for the video submission. The paper writing was started early during system design, during the process of selecting pictures. Looking at the pictures, taking new ones, writing the paper structure, having many pilot studies, and improving the prototype was part of the design process, and part of the process of thinking and creating the wearable mid-air display.

3.4 Summary of Research Contributions

The contribution of this thesis is to present a set of working prototypes, then, based on insights gained through these prototypes, to present a design space for body-centric projection (section 3.4.4). The prototypes are the result of interdisciplinary collaborations with interaction designers, computer graphics researchers, robotics enthusiasts, architects, and communication designers.

3.4.1 Environment-Centric Projection

Constructive assemblies

Form-finding prototypes explored assembly of identical blocks in paper A and paper B.

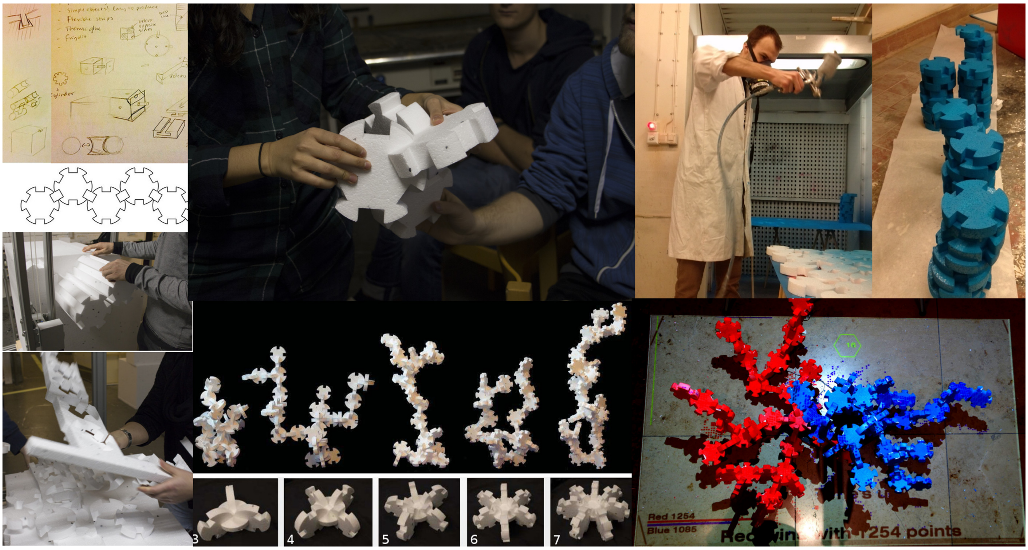

Figure 3.5: *(Left) Sketches and block fabrication process: design of units given to the CNC hotwire cutter, cylinders removed from the styrofoam block, sliced cylinders resulting in the units; (Middle) Manual unit assembly (Right) Coloring units and resulting structures from a game that employed projection mapping on structures (Paper B).*

The assembly resembles plant growth and is obtained through connecting identical blocks performed by one or two competing users. Each block type gives rise to different morphologies during each assembly session depending on the user and the environment that is augmented through projection.

In paper A the building block consisted of three rhombic cardboard plates that are connected over three shared edges constituting a rigid entity. In paper B the building block shape was explored through a family of a 2cm high styrofoam cylinders that were cut using a CNC hotwire cutter into units with different number of cogs. Figure 3.5 shows at the bottom middle the five families of blocks and the corresponding emerging structures.

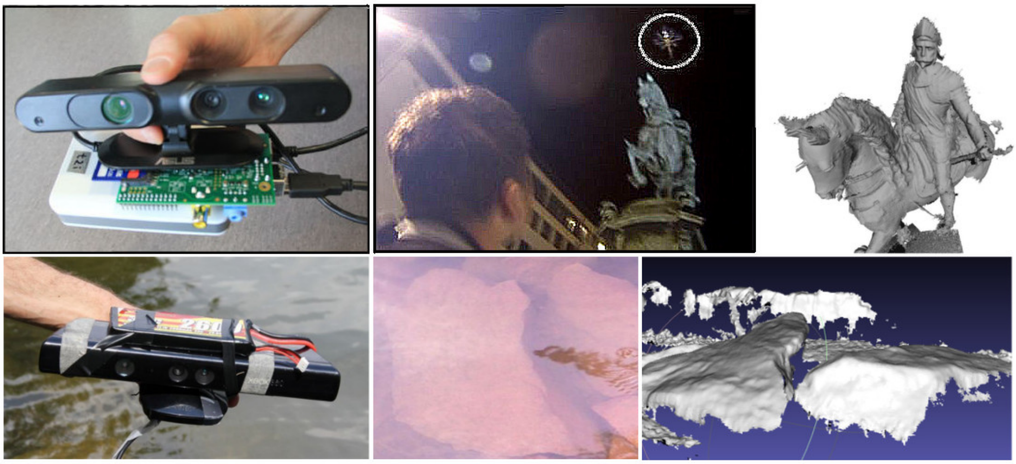

Figure 3.6: *Contributions in 3D reconstruction: octocopter-based scanning of inaccessible, hard to reach objects (top); Discovery and proof that depth sensors operate through water and are able to reconstruct underwater surfaces (bottom)*

Geometry Reconstruction

Methods for acquiring and processing geometry of objects and physical environment were employed in the first part of the thesis. However, they were presented only as tools to compute and compare states of the constructive assemblies. Experimenting with 3D reconstruction methods and their usage in new contexts has led to scientific contributions in Computer Graphics. Figure 3.6 summarizes the contexts and process of geometry acquisition: the top image depicts a reconstructed statue with the help of a depth sensor connected to a small computer fixed on an octocopter. The bottom image shows that the Kinect sensor is able to retrieve underwater surfaces.

3.4.2 Body-Centric Projection

Since mobile interactive devices are used in locomotion contexts they could be designed by taking into account common activities such as cycling and walking. Paper E and paper H explore two interfaces for the context of walking, while paper F and paper G compare two types of visual interfaces for cycling. All prototypes were evaluated for the task of map navigation. We found that for cycling a road projection was considered safer and easier to use compared with a smartphone mounted on handlebars (paper F). In the follow-up study comparing road projection with a head-up-display on bicycle we found that the HUD was considered safer and easier to use (paper G). These findings could inform, for instance, bicycle sharing services installed in cities. The visual interface of the Copenhagen City Bike (Figure 2.4) consists of a tablet computer mounted under the handlebars. Our results suggest alternatives that were considered safer and easier to use by our experiment participants. Finally, the concept of a wearable mid-air display (paper H) offers a prototype that can be used to explore new ways of using information in mid-air (cover, Figure H.1, and Figure 3.9). These prototypes are presented in the following.

Smart Flashlight

The mobile interface explored in the context of locomotion consisted of bicycle prototypes presented in paper F and paper G, and a wearable mid-air display mock-up described in paper H. The bicycle prototypes proposed replacing vehicle headlights with pico projectors and augmenting the physical space around the bikes with useful information. The application that was evaluated was map navigation in an urban environment at night time.

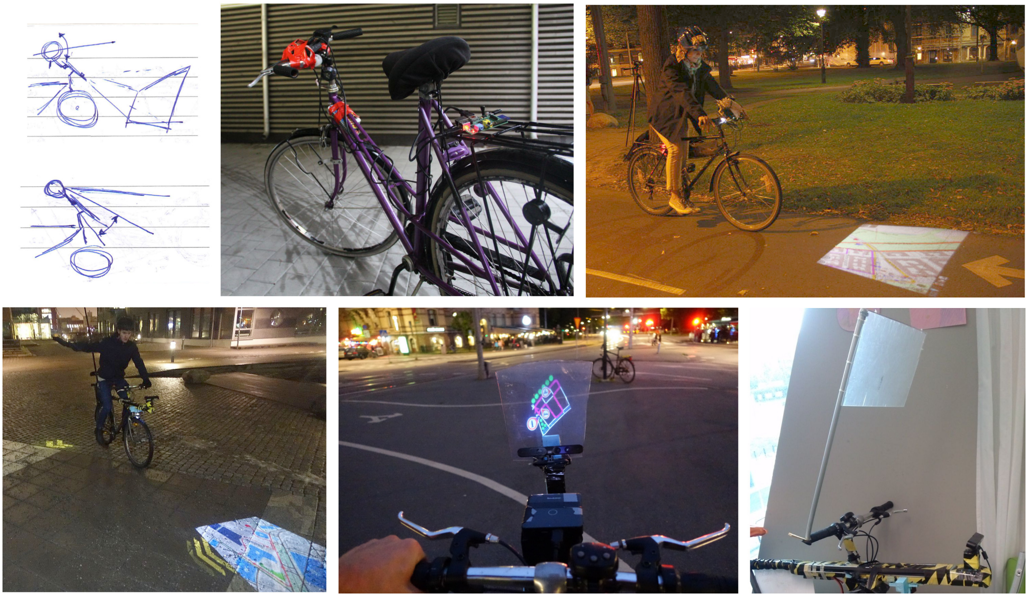

Figure 3.7: *Initial sketch and bike-mounted projector prototypes created in 2013 and 2014 for paper F (top), splitting projection space and head-up-display prototypes done in 2015 for paper G (bottom)*

The Smart Flashlight prototype (paper F) projected a map in front of the bike and compared this placement of information with a map displayed on a smartphone mounted on handlebars (Figure 3.7 top right). The first prototype that led to Smart Flashlight was developed in 2013 (Figure 3.7 top middle). It explored the concept of replacing headlights with information by detecting obstacles ahead and projecting corresponding arrows in front of the bike in order to avoid collision.

This early 2013 prototype consisted of pico projector and a depth sensor fixed on the handlebars and connected to a Raspberry Pi placed on the rear rack (Figure 3.7 top middle). This work was submitted to an international conference, but not accepted, however the valuable feedback suggesting that the depth sensor acted only as proximity sensor helped us focus and refine the concept into the second prototype. The Smart Flashlight mock-up developed in 2014 consisted of a 3D printed holder we designed for the pico projector connected to an Android smartphone held by a commercial handlebar mount. The projected display had the shape of a trapezoid, with an area of $0.72m^2$, shown one meter in front of the bike. For map navigation, the OsmAnd Android application was used because it supported loading different routes that were exchanged during the experiment. Cycling routes were created using an opensource application called Viking and Runkeeper, an application for tracking sport activities that collected information on the travelled route (distance, time, and speed).

Gesture Bike

The third bicycle prototype aimed at further developing and evaluating alternative placements of information during locomotion. First, the road projection from Smart Flashlight was compared with a head-up display (Figure 3.7 bottom middle) for the task of map navigation while cycling. Second, we proposed the concept of displaying information such as minimum stopping distance and rider "safety envelope" through projections on the road (Figure G.7). Third, we compared a gesture-enabled projection system with an off-the-shelf commercial turn signaling system (Figure 3.8).

The hardware prototype consisted of one laptop, two Brookstone pocket projectors mounted on an aluminum reinforced styrofoam extension of the frame next to a depth sensor pointing to the cyclist, a head-up display (HUD), and two mirrors that split and reflected one projection at the back of the bike (Figure G.2). The projectors were connected alternatively to a laptop fixed on the rear rack and running a OpenGL application displaying a map with the route thickened, and the current position displayed as a blue dot. The depth sensor was used to detect the gestures performed by the cyclist for signaling intention. For the HUD different materials were tested: $2mm$ thick half-transparent low density polyethylene (LDPE) and transparent plexiglass sheets mounted at a distance of $52cm$ from the handlebar (see Figure G.2). We cut the sheet as $28cm$ high trapezoids with the small base of $20cm$ and the large base of $28cm$. The sheet was then slightly bent in the form of a windshield and mounted at a $24°$ angle from the vertical (see Figure G.2). Map visibility was better with LPDE, but one could not see through it as in the case of a head-up display of a car, so we replaced it with the plexiglass. The HUD was also made removable so that it would not affect the view of the projected road display.

Based on a collaboration with a communication designer, we prototyped different map

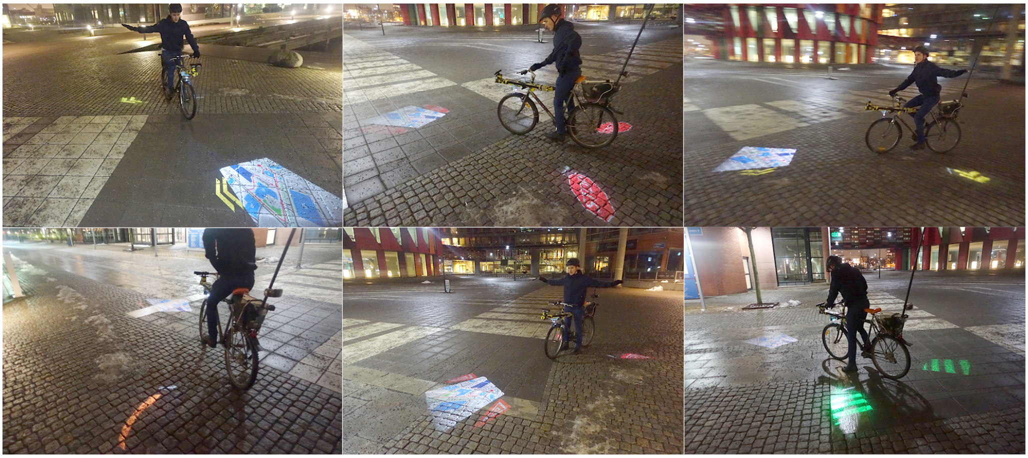

Figure 3.8: *Prototyping gestures and corresponding visual signals displayed around Gesture Bike (paper G). Top (left to right): turn left, stop, turn right. Bottom (left to right): "pass me", hazard, and awareness markers*

visualizations. The bottom left image of Figure 3.7 depicts an initial cluttered map, while the bottom middle image shows a simplified map, with a clear route and several landmarks. Incremental improvements of map visualizations were done based on projecting on different road surfaces and weather conditions. A set of principles not presented in paper G but which determined our final map visualization in our bicycle prototype interfaces includes: i) increase contrast ii) display minimal information about the route, reduce clutter e.g. fewer roads iii) add landmarks (restaurants, obelisks, trees, green areas) to help orientation iv) map background to be white so that the road projections could act as a headlight illuminating the road ahead.

The application detecting the gestures of the cyclist was based on the OpenNI framework. Figure 3.8 shows the multiple cyclist gestures that were detected and displayed around the bike. For paper G only the *left* and *right* gestures were evaluated, although the *stop* gesture was also shown in the submitted video. The following factors affected the accuracy of gesture detection: variation of body types in height and width, loose clothes, distance and angle of the depth sensor. These factors were observed during the pilot studies with many participants and helped improve the prototype and the evaluation of the system.

Wearable Mid-air Display

The idea for the wearable mid-air display protoype was based on the related work on mid-air displays and from the drawbacks of previous bicycle prototypes where projection visibility depended on the surfaces in the environment. Since the context of use for Smart Flashlight and Gesture Bike was night time cycling, a concept and prototype was developed that would have a wider context of use and be independent of environment surfaces.

We define *wearable mid-air displays* as devices that generate two-dimensional visual content that (i) floats in air, (ii) is positioned relative to a mobile user, and (iii) allows the user to determine the distance of the visual content and to interact with it.

This concept was developed through exploration of different placements on the human body for mounting small portable projectors. Several materials with different levels of transparency were explored; the images on the bottom left and middle from Figure 3.9 depict the mosquito net used for the projection that allowed the light to go through so that two displays were obtained: on the net and on the physical environment.

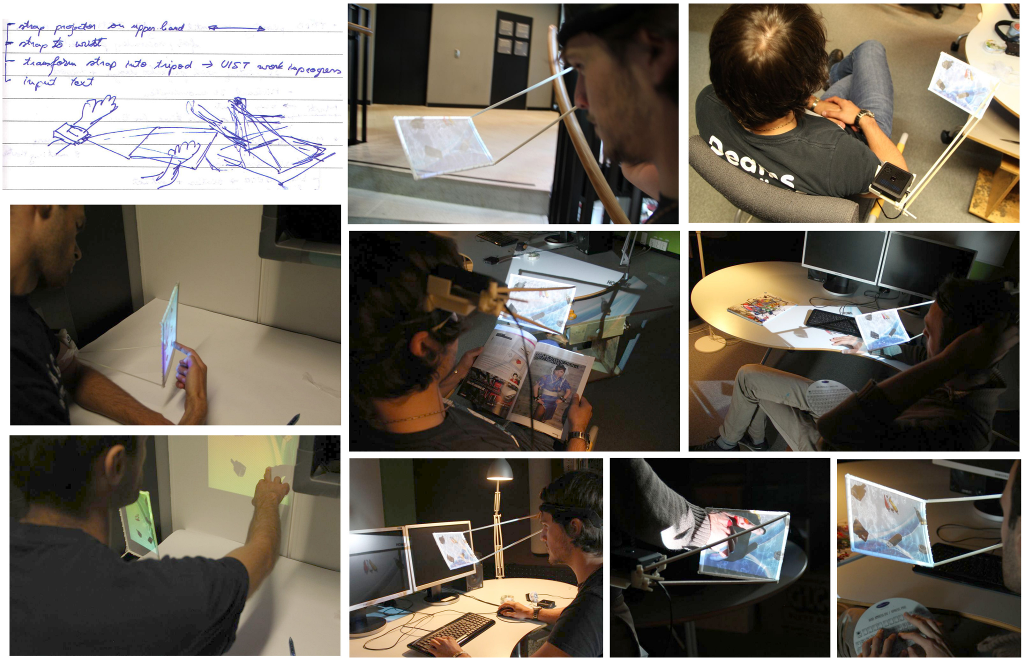

Figure 3.9: *Initial sketch (top left), followed by exploring various use cases and mounting positions of the projector and frame, leading to the wearable mid-air prototype, paper H.*

The final prototypes from paper H compared two mounts on the human body that allowed different usage modes: chest mount and wrist mount. The projector holder, frame, wrist, and chest-mounts were designed in Blender and 3D-printed. The projector holder was designed to securely slide into the wrist- and chest-mount, allowing easy switching of its position. The pico-projector PicoMax MX 60 displaying map navigation application was connected to a mobile phone. The PicoMax was smaller and less bright than the Brookstone projectors used in the bicycle prototypes. A GPS receiver was connected via Bluetooth to the phone, improving the lower location accuracy of the smartphone. The GPS navigation application was GPS Essentials, and routes were designed in the Viking software. The projection surface was a 3mm thick semi-transparent white fabric with uniform brightness, set inside a 192 × 196 mm frame. The screen was attached to the frame using hook and loop straps allowing it to be pulled out, thus preventing any distortions. Two 250 mm wooden rods, chosen for their rigidity and their low specific weight, were inserted and glued into holes in the frame corners connecting it to two holes in the projector holder (Figure H.4).

3.4.3 Articles Summary

The first two papers (A, B) are on the topic of environment projections, presenting prototypes that explore materials and form done in collaboration with the architect Stig Nielsen. The two papers (C and D) experiment with environment reconstruction in different outdoor contexts. The following four papers (E, F, G, H) explore body-centric projected interfaces used while walking and cycling, and evaluating the prototypes in urban environments.

Paper A modifies the environment within a static, limited area of projection. The dynamic environment consists of cardboard building blocks. The user adds cardboard blocks to a cluster, based on feedback projected from above, with the purpose of making a balanced structure. Rodney A. Brooks proposes a digital control system for artificial intelligence, called layered subsumption, that proves to be robust in interaction with the real world [Bro91]. We investigate how this robust layered subsumption acts both digitally and through functionality embedded in the material of the building system itself. We describe a building system with computational control over the building process, arguing how layered subsumption exists seamlessly, shared between the digital and the physical material of the system. If a system using layered subsumption is able to modify its entire environment, we argue, that subsumption must be found embedded within the morphology and material of the environment.

Paper B presents five types of constructive assemblies that emerge through a form-finding process resembling growth. The synthetic growth is obtained through the assembly of identical blocks performed by two competing users. Each block type gives rise to different morphologies during each assembly session depending on the user and the environment that is augmented through projection on the synthetic structure and around it. The digitally augmented tangible interface is evaluated with professionals and students in interaction design. Characteristics of block design, constructive assembly approaches, and further implications are discussed. This work could contribute in organic user interfaces, biologically produced architecture, and reconfigurable robotics applications.

Paper C presents two practical experimental setups for scanning and reconstructing real objects employing low-price, off-the-shelf embedded components and open-source libraries. As a test case, we scan and reconstruct a 23 m high statue using an octocopter without employing external hardware.

Paper D describes experiments in which we acquire range images of underwater surfaces with four types of depth sensors and attempt to reconstruct underwater surfaces. Two conditions are tested: acquiring range images by submersing the sensors and by holding the sensors over the water line and recording through water. We found out that only the Kinect sensor is able to acquire depth images of submersed surfaces by holding the sensor above water. We compare the reconstructed underwater geometry with meshes obtained when the surfaces were not submersed. These findings show that 3D underwater reconstruction using depth sensors is possible, despite the high water absorption of the near infrared spectrum in which these sensors operate.

Paper E explores with the help of two experiments design considerations on designing mobile projection applications. Emerging research and growing use of mobile projectors reveal a need for better understanding of how to design interaction with such devices. This paper examines key aspects affecting the use of mobile projectors during motion. With the help of two prototypes we explore visibility issues of mobile projectors, in particular how surface colors and geometry affect the visibility of projected information. We then consider the choice of placement of information in the human field of view in the context of peripersonal and extrapersonal spaces. Finally, we raise the issue of body mount location and design implications of long-term use of this type of pervasive display. The paper presents two design explorations using projected displays to address projection on outdoor regular surfaces (snow) and projection on indoor irregular surfaces (indoor and outdoor), in the form of useable prototypes presenting map navigation. Use of the prototypes was explored in various contexts, leading to insights into the limitations and possibilities of such displays. These insights are presented in a set of design considerations intended to inform designers of future mobile projector applications.

Paper F suggests that our environment could become a responsive part of the information domain. For navigation using a map while cycling in an urban environment, we studied two alternative solutions: smartphone display and projection on the road. This paper firstly demonstrates by proof-of-concept a GPS-based map navigation using a bike-mounted projector. Secondly, it implements a prototype using both a projector and a smartphone mounted on a bike, comparing them for use in a navigation system for nighttime cycling. Thirdly, it examines how visuo-spatial factors influence navigation. Our findings will be useful for designing navigation systems for bikes and even for cars, helping cyclists and drivers be more attentive to their environment while navigating, and providing useful information while moving.

Paper G suggests that interactive surfaces could be employed in urban environments to make people more aware of moving vehicles, showing drivers' intention and the subsequent position of vehicles. To explore the usage of projections while cycling, we created a system that displays a map for navigation and signals cyclist intention. The first experiment compared the task of map navigation on a display projected on a road surface in front of the bicycle with a head-up display (HUD) consisting of a projection on a windshield. The HUD system was considered safer and easier to use. In our second experiment, we used projected surfaces to implement concepts inspired by Gibson's perception theory of driving that were combined with detection of conventional cycling gestures to signal and visualize turning intention. The comparison of our system with an off-the-shelf turn signal system showed that gesture input was easier to use. A web-based follow-up study based on the recording of the two signaling systems from the perspective of participants in traffic showed that with the gesture-projector system it was easier to understand and predict the cyclist intention.

Paper H focuses on wearable mid-air displays. Advances in display technologies could soon make *wearable mid-air displays*—devices that present dynamic images floating in mid-air relative to a mobile user—available. Such devices may enable new input and output modalities compared to current mobile devices, and seamlessly offer information on the go. This paper presents a functional prototype for the purpose of understanding these modalities in more detail, including suitable applications and device placement. We first collected results from an online survey identified map navigation as one of the most desirable applications and suggested placement preferences. Based on these rankings, we built a wearable mid-air display mockup consisting of mobile phone, pico projector, and a holder frame, mountable in two alternative ways: wrist and chest. We then designed an experiment, asking participants to navigate different urban routes using map navigation displayed in mid-air. For map navigation, participants ranked wrist-mount safer than chest-mount. The experiment results validate the use of a wearable mid-air display for map navigation. Based on our online survey and experiment, we offer insights and recommendations for the design of wearable mid-air displays.

Paper I argues that the use of mobile technology now takes place in many areas of people's lives in a wide range of scenarios, for example users cycle, climb, run and even swim while interacting with devices. Conflict between locomotion and system use can reduce interaction performance and also the ability to safely move. We discuss the risks of such interaction in motion, which we argue make it desirable to design with locomotion in mind. To aid such design we present a taxonomy and framework based on two key dimensions: relation of interaction task to locomotion task, and the amount that a locomotion activity inhibits use of input and output interfaces. We accompany this with four strategies for interaction in motion. With this work, we ultimately aim to enhance our understanding of what being "mobile" actually means for interaction, and help practitioners design truly mobile interactions.

3.4.4 Dimensions for Body-centric Projection

We assumed that a mobile interactive system is a digital system where those interacting with the system are able to perform locomotion whilst interacting with it. How they move is termed the *movement activity*, such as walking or cycling. Active use of a mobile interactive system while moving is *interaction in motion*. We consider that the main utility of a mobile interfaces is for mobile tasks performed on the go and that are often found in outdoor settings. The following dimensions could inform interaction in motion:

Task and movement

From a perspective of the tasks where visual information is required, we distinguish between those that require locomotion (e.g. GPS navigation, sports applications for tracking and monitoring) and tasks that have no direct relation to movement, but may need attention while being in motion (e.g. answering the phone) [DM15].

Paper I presents a taxonomy and framework based on two key dimensions: relation of interaction task to locomotion task, and the amount that a locomotion activity inhibits use of input and output interfaces. For example, a key feature of smart watches is the ability to notify users of information such as email, SMS messages and calls. This interaction is largely unrelated to the locomotion of the user. In contrast, when developing navigation applications the locomotion of the user is more strongly related to the interaction task, it is more of an integrated movement based interaction. We define four points of interest along this dimension:

Unrelated as in our example with the notifications on the smart watches, there is no sensing of locomotion or adaptability to it.

Weakly related - locomotion and interaction are related but with no immediate system response to movement, for example looking up nearby places on maps, or tracking movement with a GPS.

Strongly related there is a real-time feedback loop between interaction and locomotion, as seen in turn by turn navigation where the interface is telling the person where to turn, and the person is feeding back to it with their movements [BL12b].

Encouragement Exertion games such as Jogging Over a Distance [MOT07] or fitness systems which directly encourage players to move, such as the Zombies Run game [Nao12], may be seen as even more highly related interaction tasks, as interaction with the system is the reason locomotion is occurring.

Figure 3.10 visualizes these properties along the dimension.

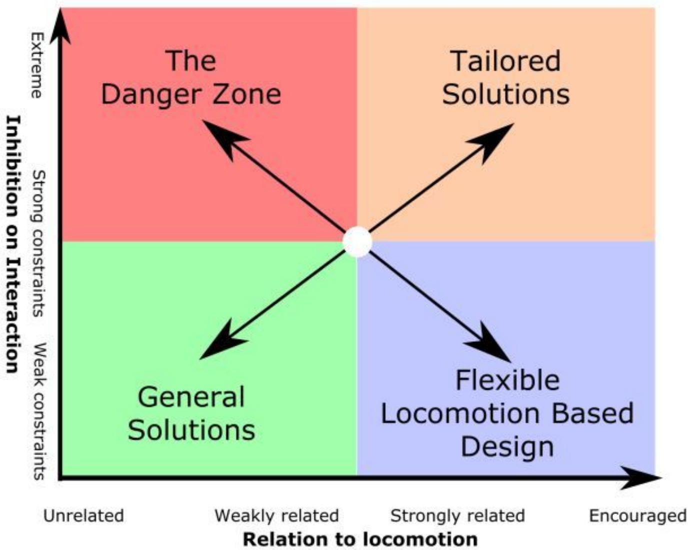

Figure 3.10: *Four strategies for interaction in motion*

Another distinction of tasks and displays, is that displays could be coupled to the vehicles that allow locomotion (head-up displays in cars, bike-mounted displays), be mounted on the body at all times (smartwatches, smart helmets, smart glasses, portable projectors), or have no relationship to the task, being completely separated from the moving body (mobile phones) (RQ3) [DM15]. For the cycling task, our study showed that the coupling of road projection to the bicycle is easier to use than a handlebar-mounted phone (RQ6, RQ7, paper F) and that it could increase safety (RQ12, paper F). In the follow-up cycling study, a head-up display was considered easier to use than road projection (RQ11, paper G). Coupling the conventional gesture for singaling turning intention on bicycles with the automatic detection of the gesture and projection on the road makes it easier to use than button input systems (RQ10, G).

Space

Humans use peripersonal space for reaching and manipulation and action-extrapersonal space for navigation [CD07b]. Environment geometry and user context could be reconstructed (RQ2, paper C, D) and augmented with information. Peripersonal space could be used to display private information, while extrapersonal spaces could be employed to display information regarding navigation (Figure 2.8). This extends human reach into the collocated space and illustrates our new ability to modify it instantly (RQ4, paper E). Coupling physical matter, block geometry, and motor skills could lead to evolving, emergent interfaces (RQ1, paper E).

Placement of information

Regarding placement of information projected on the ground in front of the walking user, from the perspective of movement variations and movement patterns, mounting the projector on a symmetry line (Figure E.1) would balance and minimize torso turn movements (RQ3 – RQ5, paper E). Regarding placement of information projected in mid-air relative to the human body, our experiments suggested that such system is considered useful (RQ11, paper H). Concerning the mounting position on the body of this wearable device generating the mid-air display, it was considered easier to use and safer if it is mounted on the wrist rather mounting it on the chest and having the display permanently in the field of view (RQ12, paper H). Regarding the cycling context comparing alternative display placements for the map navigation task such as smartphone on handlebars, road projection in front, and a head-up-display, the latter option seems to be the safest and easiest to use (RQ8-RQ10, paper F and RQ11 and RQ12, paper G).