# EXTENDING MOBILE TOUCHSCREEN INTERACTION

*Ashley Colley*

Acta Universitatis Lapponiensis 350

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LAPIN YLIOPISTO
UNIVERSITY OF LAPLAND

Rovaniemi 2017

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# Abstract

Touchscreens have become a de facto interface for mobile devices, and are penetrating further beyond their core application domain of smartphones. This work presents a design space for extending touchscreen interaction, to which new solutions may be mapped. Specific touchscreen enhancements in the domains of manual input, visual output and haptic feedback are explored and quantitative and experiental findings reported. Particular areas covered are unintentional interaction, screen locking, stereoscopic displays and picoprojection. In addition, the novel interaction approaches of finger identification and onscreen physical guides are also explored. The use of touchscreens in the domains of car dashboards and smart handbags are evaluated as domain specific use cases.

This work draws together solutions from the broad area of mobile touchscreen interaction. Fruitful directions for future research are identified, and information is provided for future researchers addressing those topics.

Keywords: Touchscreen; mobile devices; user studies; interaction design; human computer interaction.

# Tiivistelmä


Kosketusnäytöistä on muodostunut mobiililaitteiden pääasiallinen käyttöliittymä, ja ne ovat levinneet alkuperäiseltä ydinsovellusalueeltaan, matkapuhelimista, myös muihin laitteisiin. Työssä tutkitaan uusia vuorovaikutuksen, visualisoinnin ja käyttöliittymäpalautteen keinoja, jotka laajentavat perinteistä kosketusnäytön avulla tapahtuvaa vuorovaikutusta. Näihin liittyen väitöskirjassa esitetään sekä kvantitatiivisia tuloksia että uutta kartoittavia löydöksiä. Erityisesti työ tarkastelee tahatonta kosketusnäytön käyttöä, kosketusnäytön lukitusta, stereoskooppisia kosketusnäyttöjä ja pikoprojektoreiden hyödyntämistä. Lisäksi kartoitetaan uusia vuorovaikutustapoja, jotka liittyvät sormien identifioimiseen vuorovaikutuksen yhteydessä, ja fyysisiin, liikettä ohjaaviin rakenteisiin kosketusnäytöllä. Kosketusnäytön käyttöä autossa sekä osana älykästä käsilaukkua tarkastellaan esimerkkeinä käyttökonteksteista. Väitöskirjassa esitetään vuorovaikutussuunnittelun viitekehys, joka laajentaa kosketusnäyttöjen kautta tapahtuvaa vuorovaikutusta mobiililaitteen kanssa, ja johon työssä esitellyt, uudet vuorovaikutustavat voidaan sijoittaa.

Väitöskirja yhdistää kosketusnäyttöihin liittyviä käyttöliittymäsuunnittelun ratkaisuja laajalta alueelta. Työ esittelee potentiaalisia suuntaviivoja tulevaisuuden tutkimuksille ja tuo uutta tutkimustietoa, jota mobiililaitteiden vuorovaikutuksen tutkijat ja käyttöliittymäsuunnittelijat voivat hyödyntää.



Hakusanat: Kosketusnäyttö; mobiililaitteet; käyttäjätutkimus; vuorovaikutussuunnittelu; ihminen-kone-vuorovaikutus

*To Jemina, Samuel and Oskar*

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I am also grateful to the international HCI community who have accepted me into their ranks. In particular, I would like to thank professor Johannes Schöning for his guidance, enthusiasm and setting the bar for quality. Additionally, I would like to mention the contributions of Dr Keith Cheverst, and professor Florian Alt, who have both been inspirational and enabled me to make first steps in international collaboration. I would also like to thank professor Mika Ylianttila, for enabling the start of my academic research at the Center for Internet Excellence, University of Oulu. The two UBI summer schools I have attended have been key elements in my development as a researcher - I would like to thank professor Timo Ojala for the excellent organisation of these events which, positively impact the entire HCI research community.

During the process of my studies, I am very proud to have seen the growth of several young researchers, at the beginning of their careers, under the guidance of professor Häkkilä, namely Jani Väyrynen, Juho Rantakari, Lasse Virtanen, Tuomas Lappalainen and Paula Roinesalo. I hope you have gained as much from working with me as I have from working with you. Your support was essential in completing the works contained in this thesis.

I am also grateful for all my other co-authors, in alphabetical order: Dr. Florian Daiber, Olli Koskenranta, Saara Koskinen, professor Matthias Kranz, professor Antonio Krüger, Juha Matero, Kirsi Mikkonen, Dr. Minna Pakanen, Tobias Seitz, professor Frank Steinicke and Leena Ventä-Olkkonen.

At the University of Lapland I would like to thank Marjo Majava for helping me with practical matters and Satu Pesola for giving me the opportunity to work in her projects.

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Ashley Colley
Rovaniemi 9th April 2017

## Abbreviations

| | |
|---|---|
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| AR | Augmented reality |
| HCI | Human-computer interaction |
| PC | Personal computer |
| S3D | Stereoscopic 3D |
| TUI | Tangible user interfaces |
| UCD | User-centered design |
| UI | User interface |
| UX | User experience |
| VE | Virtual environment |
| VR | Virtual reality |
| VW | Virtual world |

## List of Original Publications

I Colley, A., Virtanen, L., Ojala, T., Häkkilä, J. (2016). Guided Touchscreen – Enhanced Eyes-Free Interaction. In Proceedings of the 5th ACM International Symposium on Pervasive Displays (PerDis'16). pp. 80-86. ACM.

II Matero, J., & Colley, A. (2012). Identifying unintentional touches on handheld touchscreen devices. In Proceedings of the Designing Interactive Systems Conference (DIS'12) pp. 506-509. ACM.

III Colley, A., & Häkkilä, J. (2014). Exploring finger specific touch screen interaction for mobile phone user interfaces. In Proceedings OzChi'14. pp. 539-548. ACM.

IV Colley, A., Väyrynen, J., & Häkkilä, J. (2015). In-Car Touchscreen Interaction: Comparing Standard, Finger-Specific and Multi-Finger Interaction. In Proceedings of the 4th International Symposium on Pervasive Displays. pp. 131-137. ACM.

V Colley, A., Häkkilä, J., Schöning, J., Daiber, F., Steinicke, F., Krüger, A. (2015). Touch the 3rd Dimension! Understanding Stereoscopic 3D Touchscreen Interaction. In 'The cognitive effects of spatial interaction, learning and ability'. (pp. 47-67) Springer LNCS.

VI Colley, A., Koskenranta, O., Väyrynen, J., Ventä-Olkkonen, L. & Häkkilä, J. (2014). Windows to Other Places: Exploring Solutions for Seeing through Walls using Handheld Projection. In Proceedings NordiChi'14. (pp. 127-136). ACM.

VII Colley, A., Seitz, T., Lappalainen, T., Kranz, M., Häkkilä, M. (2016) Extending the Touchscreen Pattern Lock Mechanism with Duplicated and Temporal Codes. Advances in Human-Computer Interaction, 2016.

VIII Colley, A., Pakanen, M., Koskinen, S., Mikkonen, K., & Häkkilä, J. (2016). Smart Handbag as a Wearable Public Display - Exploring Concepts and User Perceptions. In Proceedings of the 7th Augmented Human International Conference 2016 (AH'16). p. 7. ACM

In addition, the following patents by the author are presented as extensions to the academic publications, illustrating the application of the work:

P1 Colley, A. Controlling responsiveness to user inputs. US Patent App. 13/204,406

P2 Colley, A. Apparatus, method, computer program and user interface. US Patent App. 12/767,344, 2010

P3 Colley, A. Feedback Response. US Patent 20,130,082,824

P4 Colley, A., Severinkangas, KM. Apparatus, method, computer program and user interface. US Patent App. 13/446,636, 2012

P5 Colley, A. Causing display of a three dimensional graphical user interface. US Patent App. 13/455,669, 2012

P6 Colley, A., Matero, J. Method, apparatus and computer program product for user input interpretation and input error mitigation. US Patent 9,046,958, 2015

P7 Colley, A., Poikola, M, Komulainen, S. Method and apparatus for determining adjusted position for touch input. US Patent App. 12/612,476, 2009

## Author's Contributions

This thesis is based on eight original publications. In addition, seven patents (some currently at the application phase) that have been filed based on the author's research illustrate the application of the author's research. The author's contributions to the publications are as follows.

**Publication I,** *Guided Touchscreen – Enhanced Eyes-Free Interaction.* The contribution of the author in Publication I is that he has been instrumental in driving the development the concept of 'guided touch', that forms the basis for the study presented in the paper. The author made the detailed experimental design for the study, including designing the user interface, implementing the mobile applications and designing the user study process. The author also ran many of the user test sessions reported in the study. The author made all the data analysis and was the main writer of the publication. The second author (Virtanen) was responsible for creating the Perspex overlays required for the study using a laser cutter, he also ran the majority of the user test sessions and collated the results prior to analysis. The third author (Ojala) provided guidance on the positioning of the work, with the aim that the laboratory study would deliver insights that could be applied to real world contexts. The fourth author (Häkkilä) provided guidance on the user study set-up and analysis phases.

**Publication II,** *Identifying unintentional touches on handheld touchscreen devices*. In this publication the author and publication first author (Matero) contributed equally to the work. The overall concept for the study and the implementation of the mobile app, which provided the interaction use cases and logged the interactions was the work of the author. The first author (Matero) created the detailed user test process and ran all of the user tests. Both the authors contributed equally in the data analysis and paper writing.

**Publication III**, *Extending Mobile UI with Finger Specific Touchscreen Interaction.* The author made the detailed design for both studies included in the work and implemented the mobile applications utilized in both. Additionally, the author ran many of the user tests, analysed all the produced data and took the main role in writing the paper. The second author (Häkkilä) created the original concept of finger specific interaction, participated in the study planning and contributed to writing the paper. Students under the supervision of the author conducted the remainder of the user tests reported in the publication.

**Publication IV**, *In-Car Touchscreen Interaction: Comparing Standard, Finger-Specific and Multi-Finger Interaction*. The author was responsible for the design of the concept and study, including the 3 different interaction methods compared. The implementation of the prototype application, including all the graphics and software coding, was made by the author. The author made the first phase of user tests, whilst the second author (Väyrynen) carried out the second phase of testing. The author analysed the results and took the lead in writing the publication. The third author (Häkkilä) gave guidance during the study planning phase and contributed to the writing of the publication.

**Publication V**, *Touch the 3rd Dimension! Understanding Stereoscopic 3D Touchscreen Interaction.* The author was the lead author in the publication, making the majority of the publication writing. The work brings together and compares two prior studies by the authors (refer to the paper for references to the prior work). Considering the reported mobile phone based study, this was designed, implemented, analysed and a majority of the user tests carried out by the author, who also took the main part in writing the publication. Here the second and third authors (Häkkilä and Schöning) providing essential guidance on the related work in the subject area, ensuring the novel direction of the work. The remaining authors (Daiber, Steinicke and Krüger) provided the content in the tabletop domain.

**Publication VI,** *Windows to Other Places: Exploring Solutions for Seeing through Walls using Handheld Projection.* The author was responsible for the overall concept design and execution of the studies reported in the publication. The author designed the detail of the user studies, made all of the results analysis from the study results (including statistical analysis), and was the main writer of the publication. The second authors (Koskenranta) made the software implementation for both of the test configurations. The third and fourth authors (Väyrynen and Ventä-Olkkonen) carried out the majority of the user tests. The fifth author (Häkkilä) provided the vision for the see-through interaction and was a co-writer of the publication with the author.

**Publication VII,** *Extending the Touchscreen Pattern Lock Mechanism with Duplicated and Temporal Codes.* The author was the leader of the paper, he created the initial concept, implemented the test application, analysed the results and took the main part in writing the paper. Authors 2 and 3 (Seitz and Lappalainen) collaborated on the user test design and in conducting the user tests. The remaining authors (Kranz and Häkkilä) provided guidance to the positioning of the work to ensure its novelty and contributed to the writing phase.

**Publication VIII,** *Smart Handbag as a Wearable Public Display - Exploring Concepts and User Perceptions.* The high level concepts demonstrated in this publication were developed by the author in collaboration with the fifth author (Häkkilä). The detailed design of the concepts and implementation of the smart handbag software application was made by the author. The user tests reported in the paper were conducted by authors 2 - 4 (Pakanen, Koskinen, Mikkonen), who also collated the recorded data. The author was responsible for the analysis of the results from the user test. Whilst all authors contributed some text to the publication, the author was the main writer of the paper.

**Patents P1 – P7.** These seven patents / patent applications were filed as a result of the author's research work in the area of touchscreen technology at Nokia Ltd. In four of the patents the author is the sole inventor and in the remaining 3 the first author, taking the lead role in the invention and submission process. The author prepared drafts of the patent application documents, and a patent lawyer edited the final patent application submission documents.

# Table of Contents

# 1 Introduction

## 1.1 Touchscreens as the de facto standard mobile interface

Touchscreens have nowadays become the de facto format for a wide variety of human-computer interfaces. The interaction technology is widely adopted and in 2017 it is estimated that almost 2 billion touchscreen panels will be delivered (Touch panel market tracker).

### 1.1.1 Issues driving touchscreen penetration

In addition to the touchscreen's ability to support direct manipulation of visual UI elements, their adoption has been driven by a multitude of other factors, such as their flexibility, low cost and speed of interface development. Touchscreen interaction has also achieved a high degree of de facto standardization, predominantly driven by Apple's iPhone product range. Thus, interactions such as 'pinch zoom' once learnt by users, can be transferred across platforms. A testament to this is the commonly reported case of children, bought up on tablet computing devices, being dismayed when they are unable to 'pinch zoom' an image in a printed magazine.

Historically, the driving promise of touchscreen interfaces was that of direct manipulation. For example, rather than pressing + and – buttons to change the size of an on-screen object the user can directly pull and push the displayed object itself to resize it. However, at some point in their evolution, touchscreen UIs began to be used to control real-world physical interactions, remote from the touchscreen itself.

Touchscreen interfaces are nowadays used in a wide variety of interaction use cases, often replacing traditional mechanical based forms of interaction. In many application areas operators need to interact with the touchscreen interface whilst focusing their gaze elsewhere, resulting in the need for semi-blind usage of the interface. Examples of such cases range from large forestry machines, to surgeons in an operating theatre, to stage lighting control systems.

Whilst touchscreen interaction enables a huge flexibility for the interface to be cost efficiently optimized to meet the requirements of each use case, it loses many of the benefits of a mechanical control based interface. Interfaces with physical push buttons, mechanical knobs that can be rotated and sliders that can be physically moved provide a far more tangible experience than touchscreen UIs, and as a consequence reduce the requirement on the visual sense for operation. In addition to tactile feedback, provided by touching, many mechanical interfaces also provide kinaesthetic feedback to the user, requiring the user's muscles to push or pull during operation. As well as usability focused issues, traditional mechanical based interfaces often provide more hedonic experiences than provided by touchscreens, for example the feeling when turning a mechanical knob with clicks every 5 degrees. Thus, with the adoption of touchscreen interfaces some aspects that provide intrinsic pleasure, purely from the mechanics of the interaction itself have been sacrificed.

To overcome these limitations with touchscreen interfaces there has been much work on artificially recreating the haptic sensations of interacting with mechanical controls. Various approaches have been used ranging from the use of mechanical vibration, physical motion and electrostatic repulsion. Whilst such approaches have been shown to have potential to improve the touchscreen experience, they still do not reproduce the full experience provided by mechanical controls. In particular, no solutions have been proposed that enable finding a required control amongst an array of controls on a touchscreen.

In addition to being driven by the pain points of current touchscreen interaction, there exists a range of opportunities enabled by combining touchscreens with a variety of other existing and new technologies. Examples include stereoscopic 3D displays, physically morphing displays, picoprojectors, and electrostatic haptics, to name a few. Rather than simply including these technologies side-by-side in the same product, by taking a holistic view to the interaction, the touchscreen and partner technologies can be bound together creating a seamless single interactive experience.

## 1.2 Research Question, Targets and Scope

The research question driving this work is:

- What are the ways in which interaction with mobile touchscreen devices may be extended?

This is addressed through the following targets:

1. To identify the overall design space for the evolution of interaction based around mobile touchscreens.
2. To select specific evolution directions that appear to have most potential, and explore those in detail, though specific concepts, implementations and user studies.
3. Based on 1. and 2. to expand the current state of knowledge for touchscreen interaction, creating stepping-stones over which subsequent researchers and designers and may pass.

To address the topic, this work divides touchscreen interaction in to 3 aspects; visualisation, interaction and feedback (Figure 1). As its scope, this work focuses only to aspects of interaction that may be experienced visually or via the users fingers when touching the touchscreen, i.e. visual and tactile senses. Thus experiences based on or including the remaining 3 senses (olfactory, gustatory and auditory), are out-scoped.

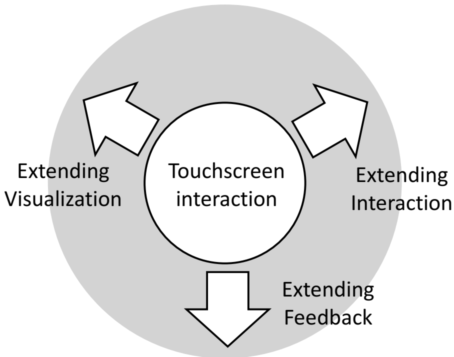


**Fig. 1.** This work aims to extend the design space of touchscreen interaction in three directions.

## 1.3 Contributions of this Thesis

This thesis provides novelty, both in its presentation of the overall design space for extending touchscreen interaction, and in its delivery of new knowledge in specific areas of the design space. This thesis is based on eight original publications, and illustrated by several patents or patent applications that have been filed based on the author's research. The contributions of the publications are presented in the following section and mapped in Fig. 2 to the presented design space.

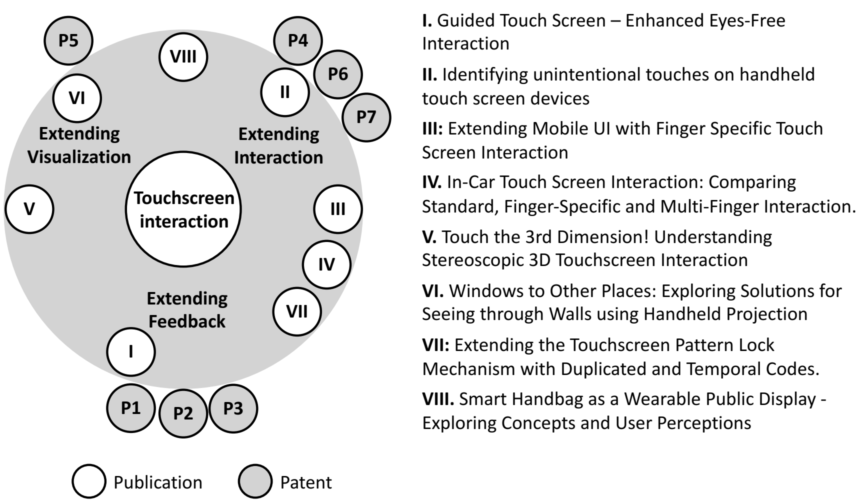


**Fig. 2.** Publications and patents mapped to the presented framework

**Publication I,** *Guided Touchscreen – Enhanced Eyes-Free Interaction,* presents a novel approach aiming to improve the usability of touchscreens in applications where eyes-free operation is a requirement. Examples being automotive UIs, factory machinery controls and interfaces used by surgeons to control tools during operations. In such contexts the user's visual focus should typically be on the physical task, rather than directed to the touchscreen. As touchscreen interfaces are now becoming common in such safety critical environments, for example in automotive dashboards[1], this research is timely.

The work examines the possibilities created by restricting the free interaction provided by touchscreens by placing a transparent Perspex overlay with cutouts on top of the touchscreen. The resultant interaction provides natural passive haptic feedback, from the edges of the cutouts in the form of both tactile and kinesthetic feedback. As by-products, this approach provides error mitigation and visual affordance of the possible interactions. Thus the solution affects to the users need to look at the touchscreen to find and interact with UI components presented on it.

The novelty of this work is that it presents the first user study exploring the use of guided touchscreen interaction for attention critical use cases. It reports on differences in user performance and user perceptions of guided touch, which enlighten potential directions for the designers of interfaces requiring eyes-free interaction.

**Publication II,** *Identifying unintentional touches on handheld touchscreen devices*, identifies and classifies accidental touches that occur when users interact with a touchscreen mobile phone. This work was triggered by the large amount of user errors reported whilst the author was working at Nokia Ltd. Errors such as accidentally starting to call a contact, or accidentally hanging up an ongoing voice call were commonly reported user issues. The work is based on a user study where users handle a touchscreen mobile device and interact with it. The data received from the touchscreen during the interactions was logged in detailed and subsequently analysed. Patterns in erroneous and intended touch interactions are identified and filters are proposed to improve the overall user experience.

The novelty of this work lies in its focus on false positives, or accidental touches, in a real device usage context. At the time of writing the paper, capacitive touchscreens were a somewhat unknown entity, and whilst other work was addressing the potential of the technology, e.g. for gesture interaction, the pain points experienced by users having the device in daily usage were unaddressed. As well as solid reference data, e.g. characterizing in detail the differences between an intentional and unintentional touch, the paper provides practical guidelines to be used by UI designers to directly improve the end user experience.

**Publication III**, *Extending Mobile UI with Finger Specific Touchscreen Interaction,* introduces one approach to extending the range of current touchscreen interactions.

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1 www.teslamotors.com/

Here, each finger on the user's hand activates a different functionality when touching the screen. The work is based around two user studies. In the first study the performance and preferences for interacting with different fingers is evaluated, to validate the general usability of the approach. Secondly, test participants interact with a mobile application that utilizes different fingers for different functions, and provide feedback on the experience.

This publication is novel in several aspects. The measurement of performance differences between different fingers when interacting with a touchscreen is novel, and provides valuable baseline data for the research community going forwards. The implementation of a functional prototype and user study based evaluation of finger specific interaction with a mobile phone is also novel, highlighting examples of the potential functionality and users' subjective opinions to those.

**Publication IV**, *In-Car Touchscreen Interaction: Comparing Standard, Finger-Specific and Multi-Finger Interaction,* extends the concept introduced in Publication III towards a real application case. The motivation for this work is timely, driven by the current introduction of touchscreens into a wide range of cars from various manufacturers. Additionally, as the usage context is safety critical the value of even small improvements in the user experience which may reduce the visual or cognitive load placed on the user is extremely high, reducing the distraction from the main task of driving the vehicle.

This publication is novel in that it provides the first user study comparing the three interaction methods in a realistic automotive UI context. Additional value is gained from the fact that the study was completed in a real car environment (although static for safety reasons).

**Publication V**, *Touch the 3rd Dimension! Understanding Stereoscopic 3D Touchscreen Interaction,* is an extension of one of the author's prior publications in the area of interaction with touchscreens including stereoscopic displays. This work brings together the author's work from the mobile domain, with that of the other authors work on interaction with stereoscopic 3D (S3D) in the touchscreen tabletop domain. Thus the publication provides a valuable overview to the area and identifies differences based on the context and scale of the application of the technology.

The publication provides previously unpublished quantitative data on the effect of a S3D display on the interaction accuracy with touchscreens. For example, reporting that for use in the mobile context touch targets should be significantly larger for an S3D touchscreen than for a standard 2D touchscreen. Similarly, the comparison between the contexts of small screen mobile and large screen tabletop, is novel. Overall the publication provides valuable information for the designer of user interfaces for devices fitted with S3D touchscreens.

**Publication VI,** *Windows to Other Places: Exploring Solutions for Seeing through Walls using Handheld Projection,* explores the potential to use pico-projection combined with a touchscreen mobile devices. The paper presents results from two studies utilizing mobile projection, the second study being the most relevant in the context of this thesis. In this study the display of a touchscreen mobile phone is augmented with a second projected display oriented at 90° to the plane of the touchscreen. The device is then used to browse a virtual 3D environment, with the combination of the two displays increasing the perceived level of immersion.

The novelty of this work lies in the previously un-presented use case of creating a virtual projected window to another real or virtual environment from a handheld projector. Additionally, the combination of a projected and touchscreen display is novel and, by leveraging the different display characteristics of the two displays, may open a variety of interesting new application areas.

**Publication VII,** *Extending the Touchscreen Pattern Lock Mechanism with Duplicated and Temporal Codes,* introduces a concept for usable touchscreen security. With the increasing amount of personal data stored in users' touchscreen devices, small advances in security present a strong practical contribution. In contrast to prior art, which has focused on security improvements at the expense of usability, this work aims for modest security improvements without reduction in usability.

The contribution of this publication is its presentation and validation in a user test, of a usable increment in touchscreen security. The findings from this work could be directly implemented to current mass-market smartphones as a software update and thus provide increased security to a very large number of users.

**Publication VII,** *Smart Handbag as a Wearable Public Display - Exploring Concepts and User Perceptions,* presents a set of concepts that focus the handbag as an interactive device. This includes concepts that both utilize the surface of the handbag as a display and concepts that complement touchscreen devices, such as smartphones, contained within the handbag.

The publication's contribution lies in its presentation of concepts in the interactive handbag design space, several of which such as the 'handbag mode' for mobile phones contained within the handbag are novel. Additionally, the presented evaluation of smart handbag concepts via a user test is novel, and provides valuable information for those continuing to develop solutions within this domain.

The following patents by the author complement the academic publications:

**P1** addresses the issue of the continuous need to lock and unlock the touchscreen during daily use, by introducing a partial lock mode.

**P2** presents novel methods of providing tactile feedback via touchscreens, for example by physical morphing of the display.

**P3** presents a solution to the specific problem of making multiple taps on a touchscreen button in rapid succession. Whilst this interaction is a mainstay of interaction with mechanical buttons, the lack of haptic feedback from touchscreens makes this relatively error prone.

**P4 and P5** present solutions aimed at improving input aspects of touchscreens. In the former the interaction richness is improved by utilising the finger contact area as part of the input parameters. The later focuses on 3D UIs, adjusting the rendering parameters to optimise direct touch interaction with displayed elements.

**P6 and P7** are patents detailing novel solutions to reduce the amount of errors when interacting with touchscreens by adapting the touch position, either based on historical data from previous interactions or by using information from sensors surrounding the touchscreen.

## 1.4 Structure of Thesis

This thesis is structured as follows:

**Chapter 1** (This chapter). Gives an introduction to the topic area and defines the targets of this thesis.

**Chapter 2** Provides the background of the area of mobile touchscreens

**Chapter 3** Presents a design space, created by the author, that serves as a basis for understating the overall potential for extending the touchscreen interaction space. Based on this framework, existing solutions may be mapped, complementary solutions may be exposed and potentially un-researched gaps can be identified. This chapter continues with a review of the prior work in the area.

**Chapter 4** Places the specific solutions studied by the author in the design space introduced in chapter 3, and identifies the key aspects of each that contribute to the scope of this thesis.

**Chapter 5** Discusses the overall contribution of the presented work, highlighting its strengths and weaknesses.

**Chapter 6** Concludes this thesis and provides an outlook on the future of this research area.

# 2 Background

## 2.1 A Brief History of Mobile Touchscreens

In the mobile domain there have been two identifiable eras in the adoption of touch-screens in to products, pre- and post- iPhone.

### 2.1.1 The Pre-iPhone Era

The history of the touchscreen interface is relatively short, (see Figure 3) with the first touchscreen being invented in 1965.

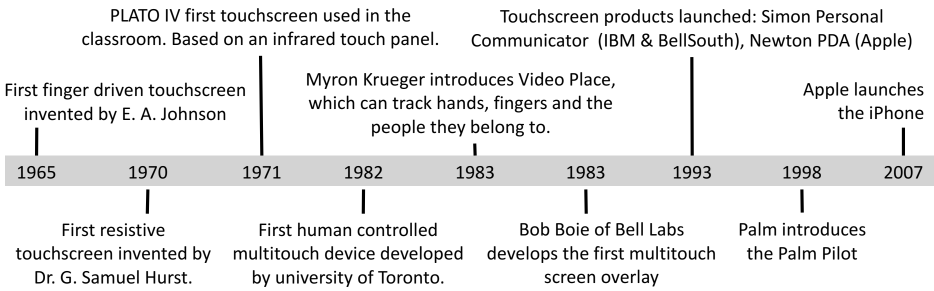


**Fig. 3.** Selected history of the touchscreen. Adapted from (ARSTechnica and Billbuxton.com)

Firstly, in the 'pre-iPhone' era (1993 – 2006), touchscreens were predominantly used as a stylus driven interface in Personal Digital Assistant (PDA) devices, examples being the Palm Pilot and the Microsoft Pocket PC. Also, this phase saw attempts to broaden the application domain for touchscreen e.g. the failed introduction the media focused Nokia Series 90 touchscreen platform (see Figure 4). These interfaces were largely driven by the interaction properties of the resistive touchscreen technology, that requires physical pressure on the screen to register a touch event. Thus, such devices were typically designed for use with a stylus as their primary usage, although as can be seem from the scale of the touchable elements in Figure 4, some devices of the era were designed with the possibility for finger based interaction for selected tasks.

Notable devices of this era that innovated beyond the basic level of touchscreen interaction are illustrated in Figure 5. For example, the Sony Ericsson P800, utilised a foldable mechanical overlay keypad to press the resistive touchscreen – thus enabling finger usage with mechanical button haptics. The Neonode range of devices, notable for their small size, utilized a novel optical based touchscreen technology, which has currently found application in e.g. e-book readers under the zForce brand.


**Fig. 4.** The Nokia Series 90 based Nokia 7710, on which the author worked as a member of the design and development team. The device was launched in November 2004. Image from gsmarena.com


**Fig. 5.** Devices with notable touchscreen interfaces from the 'pre-iPhone' era. Left: The Sony Ericsson P800 (Launched 2002). Right: The NeoNode N1 (Launched 2003). Images from gsmarena.com

Although touchscreen mobile devices had gained some market penetration by 2006 (Strategy Analytics reporting that 2% of all mobile phones had touchscreens in 2006), they still had a rather niche following. At the time it was not uncommon that a user would have both a stylus-driven touchscreen PDA and an ITU-T hard key based mobile phone.

The evolution of touchscreen handheld devices was driven in large part by the commercial availability of technical advances in the underlying enabling technology that took place during the 1990's. In the next phase of evolution capacitive touch became dominant and other technologies such as resistive touch, inductive touch (requiring a special pen to interact with the touchscreen) and optical touch (now used on e-book readers) were side-lined.

### 2.1.2 The Post-iPhone Era

The second era of mobile touchscreens began with the introduction of the Apple iPhone in 2007. The innovative user interface, based on projected capacitive touchscreen technology, changed the perception of the value of touch and bought touchscreen mobile interfaces to the mainstream. The key aspects that separated the iPhone interface from that of previous commercial products were the focus on finger usage, the introduction of gestures such as pinch-to-zoom, and responsiveness to touch that was on a level far above that of previously available devices. Interestingly, one factor that contributed to the device's performance was the selection of a screen resolution that was somewhat lower than the leading devices of the time, resulting in fewer pixels to shift. Visually, the engaging skeuomorphic icons and animations of the first iPhone UI also set it apart from the other devices of the time, providing content for marketing and also easing user adoption.

The initial iPhone UI included five touchscreen gestures in its vocabulary; single tap to select or activate an item, drag and drop to move items, swipe to scroll (up/down or left/right), pinch to zoom/shrink, and double tap to make various display changes e.g. full screen. In particular, the use of inertia in the scrolling interaction, i.e. that a scrolled list does not stop suddenly but comes to rest as if it is a physical object with mass, differentiated the iPhone UI from other commercial UIs of the time and set a precedent for the level of design detail applied to UIs in general. Of the UI features in the first iPhone UI the pinch/zoom gesture was the only one to utilize the multi-touch feature that had been invented many years earlier (see Figure 4). The onscreen keyboard of the iPhone also deserves mention, the seemingly too small to touch keys were made usable through the combination of an accurate and responsive touchscreen and dictionary based adaption.

Thus the introduction of the iPhone created a paradigm shift in mobile touchscreen interfaces, setting a new baseline for both future touchscreen products and research activities in the area. Interestingly, the shift in mobile device UIs from physical key based to touchscreen did not happen as rapidly, or was as clearly identified as it may appear in hindsight, for example in 2008 display industry sources were still predicting that by 2014 half of mobile phones would utilise a touchscreen whilst the remaining half would employ non-touchscreen interfaces (Lee, 2011). This resonates with the author's own experiences within Nokia Ltd. at a similar point in time. In practice, by 2014 all new mobile phones were touchscreen based, save for retro models targeted e.g. to the elderly.

In the remainder of this thesis the focus will be towards touchscreens based on projected capacitance technology, however in the majority of presented cases the solutions are not dependant on the specifics of the underlying technology.

## 2.2 Touchscreen Technology and Performance

Human computer interaction requires underlying technology solutions. An overview of the main technological approaches to create touchscreens and the advantages of each is presented by Bhalla et al. (2011). For example, the resistive touchscreen's poor optical performance and susceptibility to scratches are highlighted, whilst capacitive screens are noted as being suitable for harsh environments. This is by no means a complete list as many diverse approaches to touchscreen technology have been explored e.g. Han's use of total internal reflection (Han, 2005). A detailed description of the currently predominant technology, projected capacitive touch can be found in Barrett & Omote (2010). It should be noted that much of the low level processing within capacitive touchscreen solutions is propriety and not openly available, with manufacturers of touchscreen drivers, such as Atmel, Synaptics and Cypress holding the intellectual property (Atmel).

From the user experience point of view, key aspects when interacting with a touchscreen are the perceived accuracy and responsiveness to touch interactions. The majority of research in this area has focused on improving the interaction accuracy of with capacitive touchscreens (Holz & Baudisch, 2012; Potter et al. 1988). The issue of false-positives, i.e. when a user activates a function of the touchscreen accidentally, create pain points, which are critical to the overall user experience. Capacitive touchscreens are particularly susceptible to unintentional activations as they require zero-activation force. In contrast, physical buttons and resistive technology touchscreens require that some level of force is applied to trigger the interaction (Lee & Zhai, 2009) and are hence more resilient to accidental activation. It is possible to augment capacitive touchscreens with force sensing technology, and there has been much research on the topic, e.g. (Brewster & Hughes, 2009, Wilson et al., 2010, Wilson et al., 2011). However, capacitive touchscreen input with force sensing has only recently appeared in commercial products, e.g. Apple's 3D touch (Apple 3D touch), where it is used to increase the interaction vocabulary rather than address the input error resilience.

# 3 Interaction with Mobile Device Touchscreens

## 3.1 Fundamental Aspects of Touchscreen Interaction

Typically, mobile devices are not used when statically seated at a desk and hence the user will employ various hand postures to hold and interact with the device. Thus, different areas on the touchscreen will be relatively easier to interact with, depending on the device screen size, the overall weight balance and grip afforded by the device, the posture chosen by the user (i.e. one handed or two-handed interaction) and the individual user's physical parameters such as finger length and dexterity. A good introduction to the area is provided by in Wroblewski's 2012 blog posting see Figure 6 (Wroblewski, 2012). Sahami Shirazi et al. (2013) study of the posture of smartphones during interaction also provides valuable information on the actual usage of mobile devices.

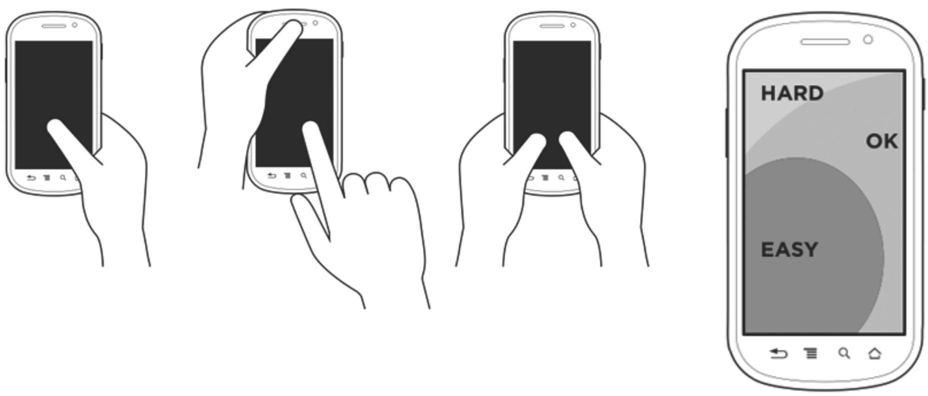


**Fig. 6.** Alternative grips and interaction approaches with a touchscreen mobile device and the approximate ease of interaction with each area of the screen. Source: Wroblewski, 2012.

The range of devices that come under the classification "mobile touchscreen devices" has expanded over recent years to include an array of wearables. In addition, many non-touchscreen wearables utilize a touchscreen smartphone as an interface, thus playing a core role in the overall product concept. An overview of the design space for wearable computing is presented by Schneegass et al. (2016).

Additionally, when used in-the-wild mobile touchscreen devices are not used in isolation and the user will often have a number of physical and cognitive restrictions e.g. caused by having to carry a bag at the same time as interacting with the device. The effect of this encumbrance has been studied by Ng et al. (2014) who report a significant decrease in input accuracy for test participants interacting with touchscreens whilst walking and carrying shopping bags.

There has been much research on finger based touch input for mobile devices. For example, research has focused on single taps has addressed e.g. minimum input target sizes, e.g. (Parhi et al., 2006) report an optimum target size of 9.6 mm for acceptable error rates for thumb based interaction with a handheld touchscreen device. Use when walking is a key requirement for mobile touch screen devices, the effect of which on input accuracy has been much studied e.g. Bergström-Lehtovirta et al. (2011), Goel et al. (2012) and Mizobuchi et al. (2005). The former noting that walking causes a major degradation in interaction performance in terms of input accuracy (Bergström-Lehtovirta et al., 2011). For text entry, i.e. using an on screen keyboard whilst walking, Goel et al. (2012) were able to adjust the input algorithms to reduce the degradation in accuracy caused by the user's motion. As well as degradations to the touch input, the ability to read the visual output of the touch screen is also degraded by walking (Schildbach & Rukzio, 2010). More recently, works by Musić and Murray-Smith, (2016) and Musić et al. (2016) have provided more detailed data on the parameters affecting touch input whilst on the move.

The work by Holtz and Baudish (2011) deserves special mention as perhaps the seminal work describing finger-based interaction with touchscreens and the sources of accuracy-based errors. Here, the so called 'fat finger' problem is introduced, whereby the thickness of the user's finger when touching the screen causes perception errors due to parallax differences between the visible upper surface of the finger and the underlying pad of the finger that is in contact with the device's screen. In a paper with an impressively large data set, Henze et al. (2011) present touch accuracy results based on 100 million individual tap events. Here a systematic offset error is noted, with taps being offset towards a point in the lower right middle of the screen. The issue of offsets is further addressed in works by Weir et al. (2012) and Buschek et al. (2013).

The following sections aim to describe the state of research in touchscreen interaction by approaching it from the directions of input, visualization and feedback. It should be noted that many of presented works contribute in more than one of these dimensions and thus they have been placed where their contribution is the largest.

## 3.2 Design Space for Touchscreen Interaction

Figure 7 presents a design space for extending touch interaction, divided into 3 main directions those of input, visual output and haptic feedback. Whilst other structures are possible, this approach matches well to a majority of enhancement approaches, such that they may be mapped to the design space. Thus, new touchscreen device concepts will potential combine enhancements from each of the directions to an overall concept. This structure is used as the framework for this thesis, firstly being applied to a literature search and secondly to the author's contributions.

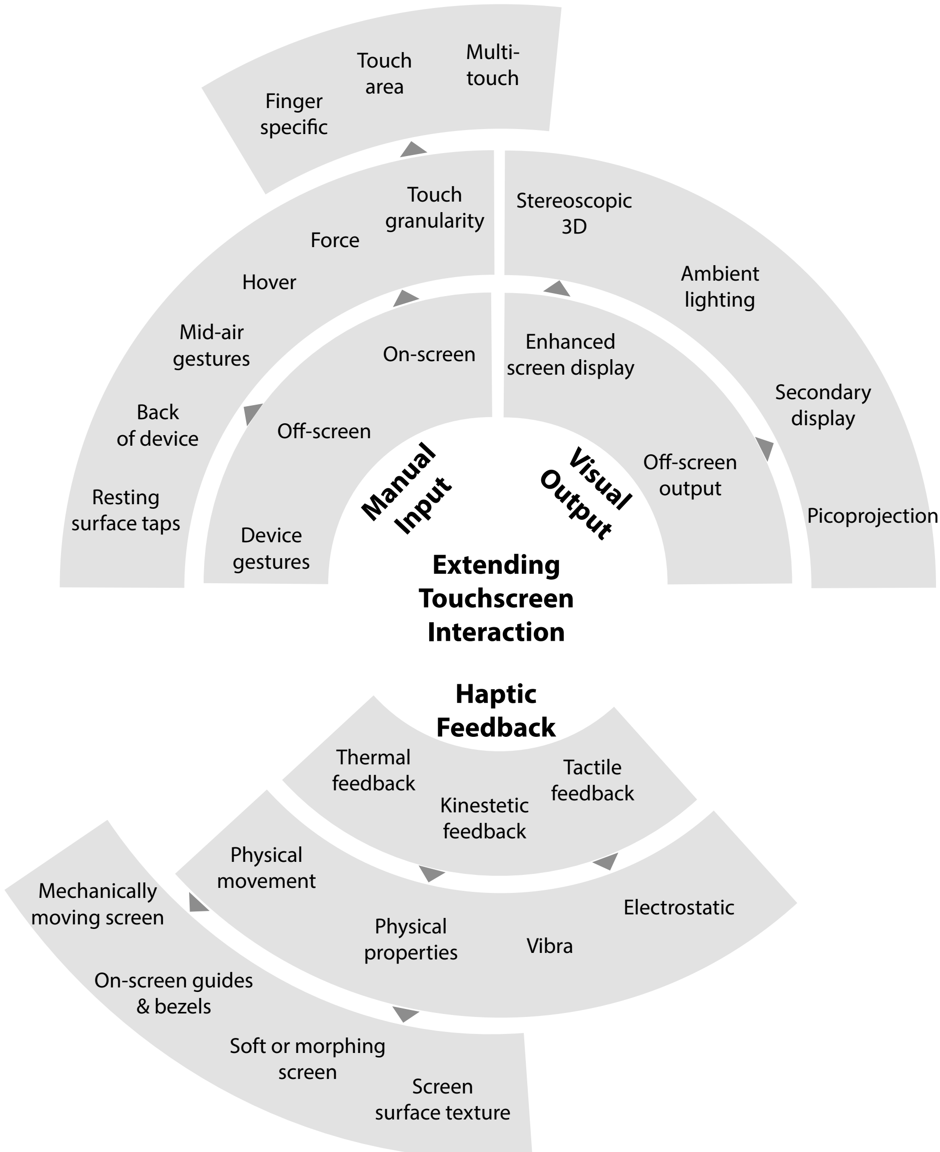


**Fig. 7.** Design space for extending touchscreen interaction (created by the author)

## 3.3 Touchscreen Input Vocabulary

### 3.3.1 Scope

Research has so far presented a huge variety of solutions aimed to either overcome limitations of basic touchscreen interaction, or extend the interaction possibilities e.g. to provide richer input possibilities. As noted previously, the scope of this thesis focuses on interaction that may be experienced via the user's fingers when touching the touchscreen itself or to straightforward extensions to that, e.g. detecting a finger hovering above the touchscreen or a finger touching the back of a touchscreen device. Figure 8 presents an overview of the input methods that are considered to fall within this scope.

In their early work on enhancing smartphone interaction Hinckley et al. (2000) provide a useful overview of the general possibilities of the design space. A prototype including an IR proximity sensor, screen bezel and device back touch sensing and tilt sensing is presented. A main conclusion is that the opportunities afforded by the additional technologies bring with them the requirement for careful design, to avoid e.g. accidental interaction.

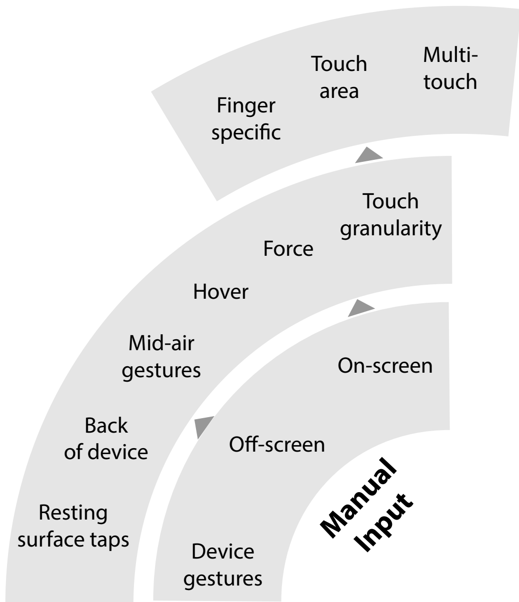


**Fig. 8.** Overview of the design space for enhancing mobile touchscreen device input

### 3.3.2 Touchscreen Input

A comprehensive body of work exists examining the input accuracy of 2D touchscreens, e.g. Holtz and Baudisch, (2010) and Parhi et al., (2006). Holtz and Baudisch summarise that inaccuracy is largely due to a "parallax" artifact between the user viewing the top of the finger whilst sensing is based on the bottom side of the finger. Considering alternative ways to detect touchscreen taps, Xu et al. (2012) explored using the accelerometer present in touchscreen smartphones as a method to detect taps (including tap position) on the device's touchscreen. Here, the work presented a Trojan application that aimed to recreate the input sensed via the touchscreen itself using the accelerometer.

The issue of false positives, or accidental interaction with the touchscreen also deserves particular mention. Typically, all mobile touchscreen devices include some form of screen locking mechanism to prevent accidental interaction, often linked with a security mechanism to prevent unauthorized device usage. As well as physical switches, solutions such as "slide to unlock", pin codes, pattern lock and biometric lock mechanisms such as fingerprints have been used. An overview of mechanisms and discussion of their usability is given by Micallef et al. (2015). Several researchers have explored non-explicit lock or identification mechanisms, based on an individual's variation in interaction, e.g. (Buschek et al., 2015).

The importance of multitouch gestures in touchscreen interaction has increased, from earlier works that included only two gestures (Moscovich & Hughes, 2006) to extensive multitouch dictionaries (Elias, et al., 2010). Additionally, other applications such as enabling precise target selection have been explored (Benko et al. 2006).

### 3.3.3 Contact Area and Finger Pose

Using the contact area of the finger or thumb touching the screen has been proposed an input parameter (Boring et al., 2012). For example, this may be used to enhance the interaction with one finger only, e.g. by rolling the finger to change the area in contact. Potential use cases are e.g. for zooming in and out when viewing photos, which may be compared with the current de facto pinch to zoom gesture which requires two finger interaction and is hence challenging to accomplish using only the hand holding the device. In a variant to this, Wang et al. (2009) present a solution that determines the orientation vector of the touching finger relative to the touchscreen by using the shape of the contact area. Here use cases include enhancing target acquisition, rotating an onscreen dial and identifying inputs from two different users. Parameters describing the touch contact area are already available from the leading commercial touchscreen driver vendors and thus such solutions could be easily bought to the mass market. This approach is further extended to three-dimensions in Rogers et al.'s Anglepose and in Kratz et al. (2013). In the latter the finger's pose, i.e. the angle of the finger touching the screen, is used as an input, e.g. to zoom in on an image or map, or to change the volume level of a media player (Kratz et al., 2013).

### 3.3.4 Hand and Finger Identification

Attaching different interaction functionality to each of the user's hands or fingers has been explored as one approach to increasing the vocabulary of touchscreen interaction. Distinguishing between individual users' hands has been explored in the context of collaborative interfaces such as tabletops. In Ramakers et al. (2012) camera-based tracking is used to distinguishing between multiple users' hands from their shape. Capacitive finger printing has been studied to identify different individuals touching the screen in Harrison et al. (2012), for example to enable different users to draw in different colours in a drawing application. An optical fingerprinting approach to user identification has also been studied by Holz and Baudisch in their Fiberio concept (Holz & Baudisch, 2013).

Distinguishing between fingers has been demonstrated by the Perkinput method in the context of touchscreen based text input (Azenkot et al., 2012), where the approach is limited to this use case and does not consider generalizing the principle for UI design. Differentiation between different parts of the hand, for example fingertip and knuckle has been presented by Harrison et al. (2011) and Lopes et al. (2011). Here, various functions are demonstrated, such as using the knuckle to open a context specific menu (c.f. mouse right click).

Utilizing different fingers for specific input events has been demonstrated in other contexts than the touchscreen e.g. in Huber, et al. (2014) and Vega & Fuks, (2014). Huber et al. (2014) present a wearable input control TeleGlove to control mobile phone calls when the user is in a cold outdoor context. Here, the call can be answered, ended and silenced with the TeleGlove by pressing two fingers together. In Vega & Fuks (2014), a prototype of fingernails employing RFID tags is presented. When each marked fingernail is brought to the RFID reader, it is recognized and used for controlling music and sound effects. However, it should be noted that both concepts do not explore use cases incorporating a touchscreen.

Outside the mobile domain, finger specific interaction has been presented by (Sugiura & Koseki, 1998; Marquardt et al., 2011; Benko et al, 2009). In their work, Sugiura & Koseki (1998) present a technical proof-of-concept level design for distinguishing between fingers by detecting fingerprints. This concept is then used e.g. to transfer data between devices 'on the fingertip'. By utilizing a special marker glove in the tabletop space, Marquardt et al. (2011) enables finger specific functionality, such as cutting with one finger and pasting with another. Benko et al. (2009) utilized muscle sensing in order to gain richer input data for interactive surfaces, and demonstrate finger-dependent painting.

### 3.3.5 Force Sensing

Sensing the force with which users touch or press the touchscreen has also been explored as a way to increase the touchscreen input vocabulary. In earlier research touch and press events have been distinguished and utilized as different input events for a mobile phone application (Holleis et al., 2008). Sheer force i.e. force tangential to the screen's surface has been evaluated by Harrison and Hudson (Harrison & Hudson, 2012) as an additional information source for touchscreen input. This provides an additional analog 2-dimensional input space for touchscreen interaction.

Wilson et al., (2010) examined the granularity of input possible via force sensing on a mobile device. Their findings indicated that selection using 10 different pressure levels was possible and performance was only marginally degraded when visual feedback was removed. The combination of touchscreen force input with walking usage has been explored by Wilson et al. (2011), using a prototype mobile phone with a force sensor attached. In this context, it was concluded that using the rate that force is applied, rather than the absolute level of force, provides a more robust interaction. The use of force sensing as a modifier for touchscreen text input provides an interesting application for the technology (Weir et al. 2014). In this case users were able to lightly press characters they were less sure about being correct, which was then used as an input parameter to the language model correcting the user's typing. Considering force type input on a wearable bracelet form factor, Pakanen et. al's (2014) 'squeezy bracelet' is of interest.

### 3.3.6 Interaction Above the Screen

The use of the smartphone's camera to identify gestures made by a finger above a smartphone is explored by Lv et al. (2013), who in addition to an implementation present a user study. The combination of on-touchscreen interaction and gestures in the air above the screen is presented by Chen et al. (2014a) in their Air+ touch concept. In a somewhat different direction, the same authors present an approach using the user's stance while interacting with the smartphone, or more specifically the distance between the user's body and the smartphone, as a parameter to augment touchscreen input (Chen, et al. 2014b). Related earlier work had studied body centric interactions in general, whereby e.g. different content is revealed on a mobile device by placing it over a certain part of the user's body (Chen et al., 2012). An overview of the possibilities (and challenges) in seamlessly combining interaction on and above a touchscreen in a continuous interaction space, is presented by Marquardt et al. (2011).

### 3.3.7 Input Outside the Touchscreen

To address limitations of small touchscreens, where the fat finger problem is most pronounced, i.e. the interacting finger obscures part of the screen area making target selection harder, back-of-device interaction has been proposed (Baudisch & Chu, 2009). Here a prototype nano-touch device with a 2.4" display was created and used to validate back of device interaction down to display sizes 1" diagonal.

Using the vibration patterns of fingers moving on textures surfaces as an input mechanism was introduced by Harrison & Hudson (2008) in their Scratch input concept. Later work applied this vibration pattern approach to back of device interaction as well as interaction via the surface on which the touchscreen device is resting, e.g. a table surface, has been studied by Zhang et al. in their Beyondtouch concept (Zhang et al., 2015). Here the smartphone's standard accelerometer, gyroscope and microphone are used e.g. to enable interaction with the device in conditions when touchscreen interaction would be challenging. In Xiao et al. (2014)'s Toffee concept, acoustic time of arrival is used to enable interaction with the table surface on which a mobile device is placed. An interesting solution in the acoustic based interaction domain is presented by Laput et al. (2015) in their Acoustruments concept. Here, acoustic guide tubes are added between a smartphone's loudspeaker and microphone, various interactions with the guide tubes are then decoded as interaction.

Magnetic pointers have also been used to extend the interaction space around the touchscreen (Harrison & Hudson 2009c; Hwang et al., 2013). In the Abracadabra concept a magnetic ring is worn on a finger to enable interaction with a very small wristwatch display (Harrison & Hudson 2009c). In the magic marionette concept (Hwang et al., 2013) magnets are attached to a smartphone via flexible rubber arms, the smartphone's magnetometer then detecting gestures based on the movement of the arms relative to the device. Interaction via objects placed on the touchscreen has also been studied (Chan et al., 2012; Yu et al., 2011; Wang, et al. 2011;). Wang et al.'s concept also provides tangible feedback via its use of flexible objects such as a rubber ball.

Whilst the majority of work has been to provide complementary alternative interactions for touchscreen devices, Wilkinson et al. utilize a wrist worn accelerometer to provide additional granularity and expressiveness to touchscreen gesture interactions (Wilkinson et al. 2016). Extending this to interaction with devices that may not include a touchscreen, Wolf et al. (2013) propose the use of a motion sensor equipped ring to enable interaction with a variety of physical objects held in the user's grasp.

Other technologies that present a potential for complementary interaction to mobile touchscreens include the use of time-domain reflectometry (Wimmer & Baudisch, 2011). Here, in a technology originally utilized for locating breaks in cables, deformation of flexible conduits based on user's touch can be detected. This is also utilized in the author's patent detailing applications of such an approach (Colley & Kosonen, 2015).

## 3.4 Feedback from Touchscreens

### 3.4.1 Drivers for Touchscreen Feedback Mechanisms

Feedback forms a critical element of all interactions. This is particularly true in the case of touchscreens, where the basic form of interaction provides only a haptic indication to the user that they have touched the glass of the screen, rather than indicating any function has been triggered. In keeping with the defined scope of this thesis, here the focus is on feedback that may be experienced via the user's fingers interacting with the touchscreen device. Hence feedback channels such as visual and audible are excluded from the current scope

Compared to interaction with mechanical buttons and controls the touchscreen does not naturally provide haptic feedback to the user interacting with the interface. A wide variety of solutions based on different technologies have been studied with the target to artificially create some form of haptic feedback to the touchscreen interface. Figure 9 presents the solution space taken as the scope of this thesis in this respect.

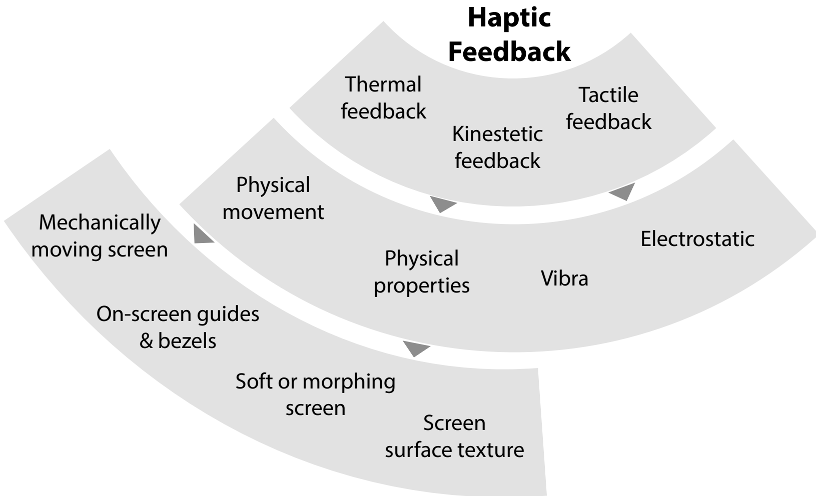


**Fig. 9.** Overview of the design space for enhancing feedback during interaction from touchscreen devices

A general background to the area of human tactile perception and tactile displays is given by Craig & Sherrick (1982). Leung et al. (2007) and Hoggan et al. (2008) highlight that, in general, adding haptic feedback to touchscreens improves user performance. Comparison between physical and touchscreen buttons has been one direction of research (Koskinen et al., 2008; Lee & Zhai, 2009). Koskinen et al. (2008) aiming to find the most pleasant vibra motor based haptic feedback, whilst Lee & Zhai (2009) target to mimic the experience of the physical button. The addition of haptic feedback has also been demonstrated to reduce the amount of time users needed to look at the screen when interacting with a scrolling UI (Pasquero & Hayward, 2011).

Key application areas that have been addressed by research include touchscreen use by visually impaired users, for example creating virtual Braille (Rantala et al., 2009; Jayant et al., 2010) and applications where eyes-free interaction is required, e.g. automobile UIs (Richter et al., 2010). Considering an in-vehicle touchscreen UI, Richter et al. (2010) combined a force-sensitive touchscreen with haptic feedback, reporting reduced error rates and shorter input times.

### 3.4.2 Vibra and Electrostatic Haptic Feedback

An early work in the area of mobile device haptic feedback was Chang et al.'s (2002) vibrotactile sleeve that could be fitted to a mobile phone, the *Comtouch*. Here, the concept aimed to augment a voice conversation by enabling the grip of one party in the call to be felt by the other party as vibrations. Other early work on vibrotactile feedback for mobile devices was made by (Brewster & Brown, 2004; Kaaresoja et al., 2006; Brown et al. 2006). Brewster & Brown (2004) present an introduction to *Tactons* as tactile messages. Augmenting touchscreen based interactions with haptics, such as a keypad entry, text selection, scrolling, and drag and drop is detailed by Kaaresoja et al. (2006). In Brown et al. (2006) the haptic feedback is delivered via vibra actuators fitted to the user's lower arm. Taking an alternative approach to the usual positive haptic feedback, Parikh and Esposito (2012) studied the use of negative vibra feedback for touchscreen use, i.e. providing a vibra pulse when ambiguous interaction was detected. In Shoogle (Williamson et al., 2007) vibra based haptic feedback is created when the mobile device is shaken, simulating the feeling of balls within the device, e.g. representing the number of received text messages.

The use of electrotactile feedback on handheld touchscreen devices has been demonstrated by (Bau et al. 2010; Altinsoy & Merchel, 2012). In their TeslaTouch work, Bau et al. present a user study comparing electrovibration and mechanical vibrotactile feedback (Bau et al. 2010).

### 3.4.3 Other Feedback Mechanisms

Various other feedback mechanisms for interaction such as thermal and airborne ultrasound have also been explored. Thermal feedback for mobile/handheld devices has been so far of relatively low interest, for example Wilson et al. (2011) and Löchtefeld et al. (2017) examples of the few works in the area. The use of airborne ultrasound has been studied as a way to provide mid-air haptic sensations (Iwamoto, et al. 2008).

### 3.4.4 Screen Texture and Morphing

The possibility to dynamically create physical buttons and other UI elements using a physically deformable touchscreen has been presented by Harrison, & Hudson (2009a). Here the approach is based on the use of pneumatically inflated chambers within a layered touchscreen construction to create the physical topology. In a user test, participants considered the raised buttons to perform both objectively and subjectively better than a flat screen. In addition, the topological screen resulted in participants needing to make fewer glances at the display surface. Similar to Harrison & Hudson, Jansen et al.'s MudPad concept provides localized haptic feedback on multitouchscreens using a magnetic fluid overlay (Jansen et al., 2010). Pneumatic screen morphing solutions are commercially available from Tactus (Tactus).

To dynamically create different touchscreen textures using a passive approach Harrison & Hudson have explored the use of stretchable materials, such as a ribbed elastic cloth (Harrison & Hudson, 2009b). By stretching and relaxing the cloth the density of the ribbing is adjusted and thus presents a different texture to users interacting with it.

### 3.4.5 Screen Bezels and Mechanical Feedback

When touchscreen interaction was first introduced to mass consumer markets in the late 1990's in devices such as the Palm Pilot, one focus of the interaction was to the edges of the screen. This was driven by the raised bezel surrounding the screen and the ease with which it was possible to move the interacting pen or finger to the screen edge. The use of bezel-based interaction with touchscreens has been studied by Blasko and Feiner (2004) who introduced tactile landmarks to the bezels of touchscreen watches. More recently, Jain and Balakrishnan (2012) revisited touchscreen bezel menus, focusing towards them as an enabler for semi-blind usage in mobile devices. In their Touchplates concept, Kane et al. (2013) explored the use of overlays to aid visually impaired users in the use of touchscreen interfaces. Here, a variety of clear acrylic overlays, such as those for with cut-outs for the keys in qwerty keyboards and a mouse, were demonstrated on a touchscreen tabletop touchscreen. The use of an active stylus to provide haptic feedback for touchscreen usage has been presented by Kyung et al. (2009).

### 3.4.6 Visually and Physically Impaired Users

When considering touchscreen usage by visually and physically impaired users, feedback for the ongoing interaction is perhaps the most critical of the dimensions (input, feedback, output) that should be addressed when aiming to improve user experience. Much work on touchscreen use has taken the visually and physically impaired as a target user group. Taking a novel methodology, Anthony et al. (2013) analysed 187 YouTube videos featuring touchscreen use by people with motor impairments, finding that, whilst users with motor impairments find the devices empowering, accessibility issues exist.

Touchscreen use by the elderly has been often studied (Page, 2014; Motti, et al., 2013). In a literature review Motti, et al. (2013) conclude that the use of touchscreen devices by the elderly requires further research and highlight particular areas that should be targeted to meet the changing capabilities with age. In a small study, Lippincott et al. (2011) found that elderly participants appreciated the possibility to use a stylus when interacting with a touchscreen smartphone. In Yamawaki & Seiichi (2012) a small camera is attached to the user's fingertip and UI elements are replaced with colour barcodes, feedback on the finger's position above the touchscreen being given to the user e.g. audibly.

## 3.5 Touchscreen Visual Output

### 3.5.1 Scope

As a fundamental part of its being, a touchscreen is a visual display, and typically in the case of mobile touchscreen devices a relatively small size display. The evolution of mobile touchscreen devices has seen the range of display sizes expand to encompass large tablet devices and small smartwatch size touchscreen devices. Additionally, the general optical performance of displays used in touchscreen devices has improved over the years, for example the resolution of iPhone displays has increased from 320×480 pixels (163 ppi) in the first versions to 1920×1080 pixels (401 ppi) in the most current iPhone 6 plus models. In parallel with this evolution, research has explored other directions to enhance the visual output from touchscreen devices, Figure 10 summarizes this solution space and the current state of research in this respect is detailed in the following sections.

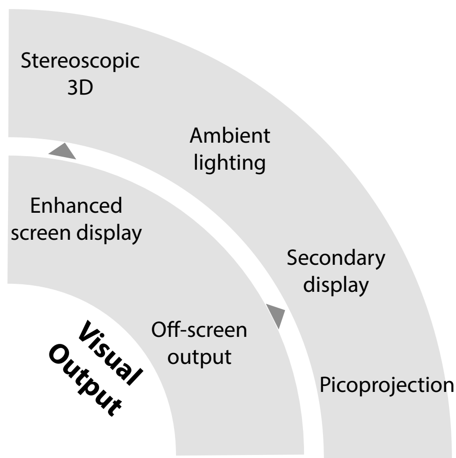


**Fig. 10.** Overview of the design space for enhancing visual output from touchscreen devices

### 3.5.2 Stereoscopic Displays

One approach to enhance the output space of mobile touchscreen devices is to utilize a display capable of delivering stereoscopic depth information to the user. Autostereoscopic mobile 3D displays, where no special glasses are needed to experience the 3D effect, can be found in 3D cameras, mobile phones and portable game consoles (e.g. Nintendo 3DS). In general 3D displays provide new degrees of freedom for UI design in the sense of the illusion of depth. With negative disparity (or parallax), the UI elements appear to float in front of the screen, and with positive disparity (or parallax), the UI elements appears behind the screen level.

Valkov et al., (2010, 2011), identified the challenges of combining touchscreen input with large 3D displays, and identified methods by which users' adapt to work around these. Despite these limitations, S3D displays are becoming more commonplace in a variety of mobile touch-screen devices. As a fundamental part of mobile device usage is its use in a non-static context, the implications of mobility on the user experience of S3D devices are critical to understand (e.g. in terms of touch accuracy and perception). Research has shown that using a device when mobile negatively affects the interaction with the device (Bergström-Lehtovirta et al., 2011; Oulasvirta et al., 2005). On the functionality side, there have been proposals that object depth within S3D UIs should be considered as an informative parameter (Häkkilä et al., 2012; Sunnari et al., 2012), and using S3D, e.g. for grouping items or highlighting contextual information, has been suggested (Ventä-Olkkonen et al., 2013). However, this work has generally not considered the usability of such designs beyond the static laboratory environment.

HCI research on S3D has so far focused on visual ergonomics, with visual comfort being investigated in several studies (see e.g. Kooi and Toet, 2004; Lambooij et al., 2007; Pölönen et al., 2011). So far, interaction with S3D mobile devices has received less attention. When investigating mobile S3D UIs, the emphasis has been on the output rather than on interaction. Pölönen et al., (2011), report that the perceived depth is less sensitive to changes in the ambient illumination level than perceived naturalness and overall image quality. Mizobuchi et al., (2008), report that S3D text legibility was better when text was presented at zero disparity on a sinking background when compared to presenting it hovering on a background image that was presented in zero disparity. It has been also pointed out that scaling the S3D content to different size displays is not straightforward, and has an effect to the perceptual qualities (Benzeroual et al., 2012). The role of visual cues has been investigated. In regard to that topic, Mikkola et al. (2010), reveal that stereoscopic visual cues with a mobile device work better than 2D ones. Huhtala et al. (2011), report that for a find-and-select task in a S3D mobile photo gallery, both the performance and subjective satisfaction were better when the stereoscopic effect was combined with another visual effect, dimming.

Taking a wider view to S3D UI design, a few papers have investigated the user experience with S3D mobile devices. Jumisko-Pyykkö et al. (2011), studied the quality of experience with mobile S3D videos, and discovered that the quality of experience was constructed from the following: visual quality, viewing experience, content, and quality of other modalities and their interactions. Sunnari et al. (2012), evaluated the S3D mobile UX design of a commercial product with a user study, where 12 users compared the S3D and 2D menus of an S3D mobile phone. The S3D menu design was seen as visually pleasant and entertaining, but lacking in usability, and the participants had difficulties seeing any practical benefit of using stereoscopy. In order to gain other than just hedonistic value, stereoscopy should be incorporated to the mobile UI in a way that it improves not only the visual design, but also the usability (Häkkilä et al., 2012).

### 3.5.3 Ambient Lighting and Secondary Displays

The use of lighting as an output in addition to, or complementary to, the touchscreen display has been researched in various forms. In the Sparkle concept (Müller et al., 2014) use lighting placed around the screen to identify items that are off the currently visible display area. A similar approach was used in earlier work (Qin et al., 2011), in this case utilising the back and sides of the device for the ambient lighting. Löchtefeld et al. (2014) extend the concept further with the addition of thermal output in the screen border lighting area.

Considering complementary wearables, Poppinga et al. (2012) use ambient lighting in the periphery of vision in their spectacles based AmbiGlasses and Burns et al. (2012) present a prototype for an ambient wrist-display showing friends' physical activity levels. A later work in a similar direction, considering glancability of wrist-worn activity displays is described in Gouveia et al. (2016). Incorporating displays directly in clothing has also been researched, e.g. Devendorf et al. (2016) reporting on user perceptions towards woven graphic elements.

### 3.5.4 Picoprojectors

The use of picoprojectors is an obvious complement to the output space of mobile touchscreen devices, considering the size and portability requirements inherent in such devices. There is a large amount of existing research on mobile projection, a good overview of the current state being provided by Wolf et al. (2016).

Rukzio et al. have investigated the interaction design space around personal projection (Rukzio et al., 2012) and research has pointed out that mobile projector technology has potential for use in various different application areas (Dachselt et al., 2012). Mobile projection has been used to augment physical objects, such as maps (Löchtefeld et al., 2009), by projecting digital information on top of them. Winkler et al. (Winkler et al., 2011) proposed a mobile phone attached projector for projecting content on to a table and sharing it with the person in the call. The Sixth Sense (sixthsense) project illustrated several possible concepts e.g. for creating ad-hoc user interfaces with a mobile projector unit, and Molyneaux et al. (2012) have extensively studied environment-aware projection for infrastructure-based and infrastructure-less cases. Mobile projection has also been reported to engage with playful interaction (Greaves et al., 2009).

In OmniTouch, Harrison et al. (2011) present a solution that uses a shoulder-mounted pico-projector to project a UI on to, e.g., the user's hand. Here, a depth camera is used to enable pre-distortion of the projected UI image, such that it appears undistorted on the projection surface. Additionally, the depth camera is also used to enable interaction with the projected UI, by tracking interacting fingers. The basis for presenting an undistorted projected image on non-flat surfaces is also presented in iLamps work by Raskar et al. (2003).

Multi-user handheld projection has been studied by Willis et al. (2011) and Xiang et al. (2007). In Willis et al. (2011) invisible infrared fiducial markers are projected along with the visible images which are used to both enable correction of the projected image and to convey information between the users' devices. Xiang et al. (2007) define a wide range of applications for two handheld projectors, including the possibility of different projectors pointing at different projection surfaces and creating multiple views.

Projection of different information spaces on different surfaces is also raised by Xiang & Balakrishnan (2006). In this case a single projected display is used, and hence the different information spaces must be viewed sequentially, rather than simultaneously. Interaction based on natural pointing of a handheld projector is explored in Winkler et al. (2012) and further in Willis et al.'s MotionBeam concept (Willis et al., 2011). In MotionBeam a projected cartoon character is animated based on the natural movement of the handheld projector. The use of personal projection in typical mobile phone usage contexts is presented in Winker et al. and Dancu et al.'s work (Winkler et al., 2014; Dancu et al., 2015). Examples of the use cases presented are; projecting navigation instructions on the pavement and projecting received text messages on the user's palm.

# 4 Extending Touchscreen Interaction

## 4.1 Approach

To explore the possibilities to extend touchscreen interaction studies were made that focusing on each of the directions identified in the author's framework for extending touchscreen interaction (See Figure 7). These studies, documented and reported as academic papers, are complemented by inventions in each of the areas created by the author and documented as patents. In the following section the extensions in each of the areas; input, visual output, and haptic feedback made by the author are presented.

## 4.2 Establishing a Baseline

To establish a baseline for this work, studies focusing towards the fundamentals of touchscreen interaction were undertaken. Here the aim was to establish how users interact with touchscreens, in particular related to the accuracy with which they can activate touch targets on the screen.

### 4.2.1 Touchscreen Performance

Around the time that the first iPhone touch interface was introduced (2007) it became clear that not all mobile touchscreens were the same. The overall user experience of using some touchscreen devices was far better than others. This difference was largely driven by two factors, 1) the perceived accuracy with which the user could tap targets on the screen, 2) the responsiveness of the UI to the user's touches. Whilst working at Nokia, the author conducted a range of studies measuring touchscreen accuracy, a particular target being improve the perceived accuracy by introducing offset values that adjusted the touch coordinated registered by the touchscreen to match those perceived by the user. This unpublished work was carried out by the author on Nokia's touchscreen devices at the time as a matter of process. It was noted that; 1) differences existed between different device models, based on a variety of factors, 2) the required offset values were mostly in the vertical direction and were not the same at all points on the screen, 3) although the offsets were small, i.e. fractions of mm, they made a notable difference to the UX e.g. when entering text using an onscreen keyboard, target sizes are small and are pressed hundreds of times during a text entry task. In addition, 4) users became accustomed to particular offsets and began to compensate. This was noticed based on user feedback when updates to offset values were made.

#### 4.2.2 Fine Tuning Touch Input

Three of the author's works are presented in this section, addressing approaches to improve touchscreen input. The publications focus on improving the accuracy of touch and on reduction of accidental touches being registered.

As identified in prior work (Holtz & Baudisch, 2010), the parallax error caused by the thickness of the finger touching the display is one cause of touch inaccuracy. As one approach to address this, Patent P7 "Method and apparatus for determining adjusted position for touch input" identifies which hand is being used to interact with the touchscreen, based on the direction of approach of the touching finger, and dynamically adjusts the touchpoint to compensate. Figure 11 illustrates the difference in error for left and right handed use. The patent proposes various methods of sensing the approach, e.g. using sensors in the bezel surrounding the screen.

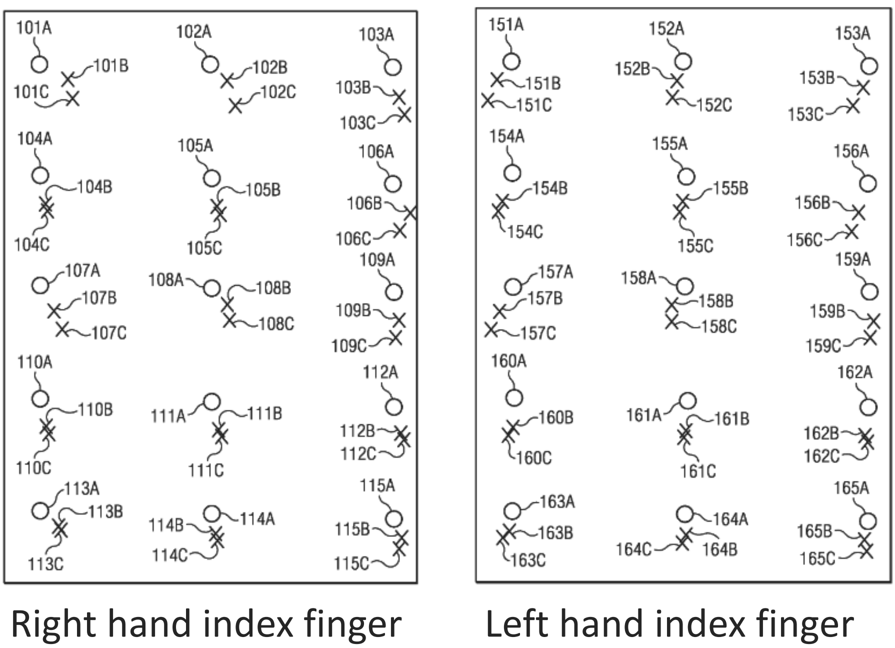


**Fig. 11.** Different errors caused by using left or right hand to interact with a touchscreen. The circles represent the visual targets and the crosses the actual positions where users tapped the screen. It may be observed that the right hand taps too far to the right, whilst the left hand too far to the left of the visual target position (From Patent P7).

Thus, based on the interacting hand, an offset may be applied to the touchpoint registered by the touchscreen such that the perceived accuracy of the touchscreen is increased. Considering the typical use cases of mobile devices, e.g. when the user is encumbered with other artifacts such as bags and keys, it is frequently the case that interaction happens with the user's non-dominant hand.

A particular pain point for mobile touchscreen interface users is the susceptibility of the interface to accidental activation i.e. by unintended touches. Many of these touches happen whilst the user is handing the device, e.g. taking it from a pocket, plugging it into a charger or changing ears during a phone call. To quantify these issues a study was undertaken whereby test participants performed typical smartphone handling tasks, during which accidental touches to the screen were logged. As a baseline participants then interacted purposefully with touch targets presented on the smartphone screen. This work is presented in Publication II 'Identifying unintentional touches on handheld touchscreen devices'. Figure 12 presents an example of the findings.

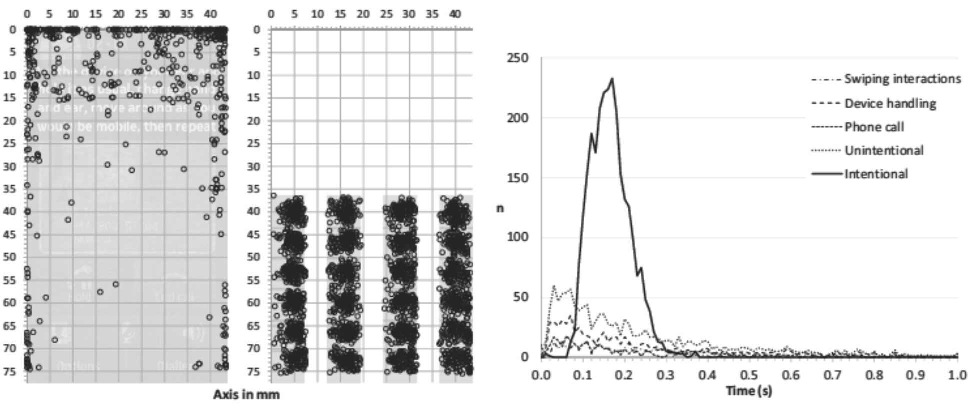


**Fig. 12.** Left: Accidental touches during a phone call. Center: Purposeful touches on a 4 x 6 grid of on screen buttons. Right: Comparing the time the finger is in contact with the screen for intentional and unintentional touches. (From Publication II).

The key findings from publication II were a set of parameters aiming to classify intentional vs. unintentional touches. For example, the time that a finger is in contact with the screen during an intentional tap interaction was found to be typically between 70 ms and 400 ms, whereas unintentional, accidental touches often are in contact for shorter or longer times than this window (Figure 12, Right). A filter function was created, aiming to reduce the amount of unintentional touches (false positives), without affecting the registration of intentional touches (true positives). Based on the collected data set, a time-window filter would reject 55.1% of unintentional touches, whilst only rejecting 0.3% of intentional touches. When filters from multiple parameters were combined, e.g. position of the tap from the edge of the device, amount of movement of touch coordinate during the tap, etc., the combined filter would reject 79.6% of unintentional touches, whilst having minimal effect on the intentional touch performance, reducing it by 0.8%.

Such filtering solutions could potentially be available for the application developers of mobile applications, who could select the strength of filtering to use depending on the use case of each view in the UI. For example, in a telephony UI view, the consequence of an accidental interaction is high. In such a view the developer would select to use a high strength of unintentional touch filtering, compared e.g. to a drawing application.

The concept of a UI tuneable touch filtering function was further expanded by the author in Patent P6. Here, a touchscreen input architecture is defined where all touch events are first processed by a mediation function before being sent to the foreground application as input. The mediation function enables the application designer to e.g. specify high and low priority areas of each view of the application. When touches in a low priority area are detected, the mediation layer delays passing the events forwards and collects other information to determine with more certainty if the original touch event is intentional or not. For example, the occurrence of other touch events or the way in which the original touch event progresses may provide additional data on the efficacy of the touch event. Taking the concept further, the proposed mediation functionality introduces the possibility for each interaction component on the UI to handle accepting or rejecting touch events, based on parameters which are dynamically tuned e.g. based on erroneous touch events (see Figure 13). Erroneous touch events may be recognized from the user's behaviour, e.g. deleting an erroneously entered character, or quickly returning from an erroneously activated view. In this way the device's touchscreen interface becomes tuned to the individual user's interaction approach and the performance becomes optimized over time.

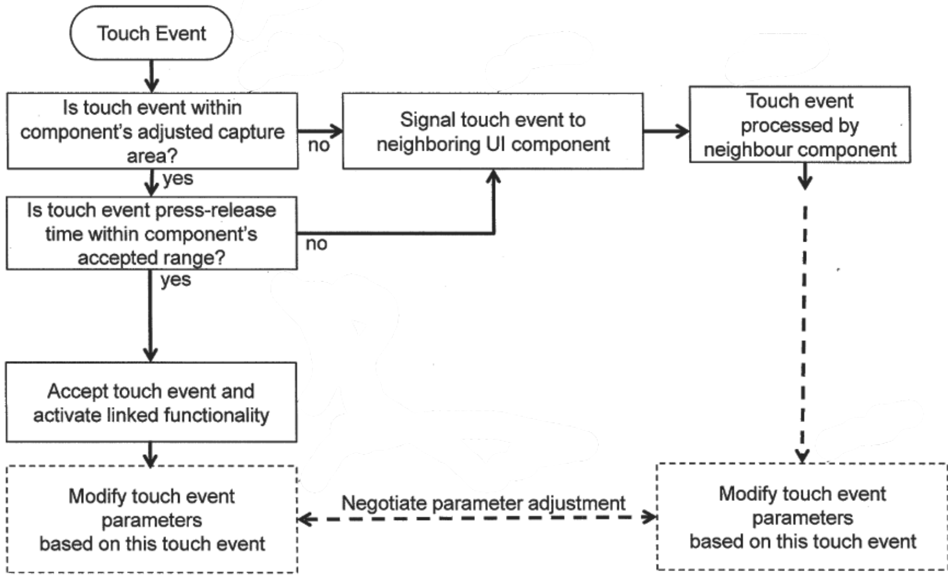


**Fig. 13.** Process by which individual UI components can modify their touch parameters to improve overall user experience. (From Patent P6).

## 4.3 Extending Input Mechanisms

Interaction in general has two sides, input and output. In this section, approaches aiming to enhance the input side of the interaction are addressed. In particular approaches that extract more granularity from each event when a user's finger contacts the touchscreen are studied. Two works are presented. In the first, the shape of the contact area of the user's finger with the screen is utilized, whilst the second attaches different functionalities to each of the user's fingers. This section concludes with two case studies focusing on the touchscreen input, firstly looking at a lock mechanism for touchscreens and secondly at touchscreen use as a car dashboard.

### 4.3.1 Utilizing Touch Area

Typically, the output from a single touch on a touchscreen is understood as being a single x,y coordinate. However, this point value has been calculated from the larger area of the user's finger in contact with the touchscreen. The majority of commercial touchscreen controllers provide information on this larger area in some form, e.g. as height and width values, or as size and angle. One interesting approach to extend the touchscreen interactions library is to utilize this additional contact area shape information as an input parameter.

Patent P4 presents a variety of possible use cases where the area of the finger's contact with the screen is utilized as an input parameter. Work based on the same approach was published by Boring et al. in their 'Fat finger' paper (Boring et al., 2012) around the same time as the author's publication. In terms of potential use cases this approach has much in common with the well-known 'long-press' touchscreen interaction, however this area based approach does not suffer from the dwell time needed to distinguish a long-press from a normal press. Similarly, 'double-tap' is an interaction overload approach that may be replaced with the touch area based approach. Figure 14 presents an overview of two of the use cases presented in Patent P4.

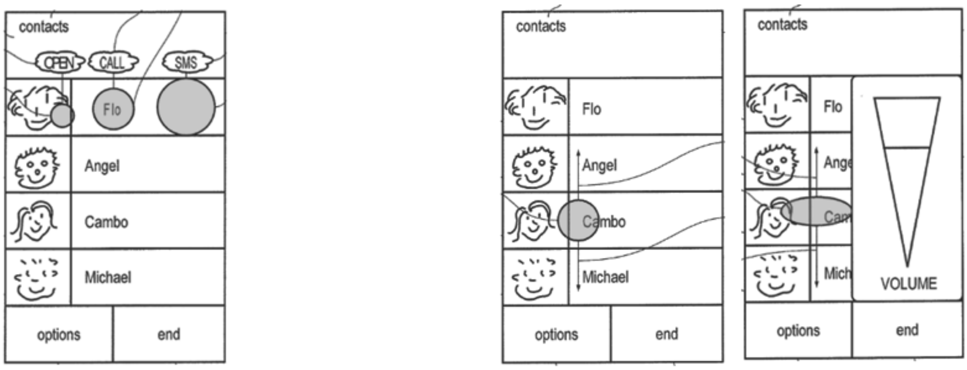


**Fig. 14.** Example interactions using touch area and shape. Left: Different sizes of touch contact area trigger different functionalities on release e.g. opening the tapped contact, initiating a phone call to the tapped contact and sending a text message to the contact. Right: Different shapes of touch area perform different functions when dragged, e.g. a circular area scrolls a list, whilst a horizontal area adjusts the device volume level. (From Patent P4).

It may be noted that, although based on a different technological solution, some of the proposed features described in this section were introduced as part of Apple's 3D touch feature on the iPhone, introduced in 2015 (Apple 3D Touch). The author's patent application, filed in April 2012 and Boring et al. (2012) predate this by several years.

### 4.3.2 Distinguishing Between Fingers

The human hand is capable of a wide variety of complex interactions with objects. However, when used to interact with touchscreens it is typically reduced to the same level of functionality of a short wooden stick, poking at the screen. The use of touchscreen gestures presents one approach to capture the potential of the human hand, and gestures such as 'pinch-to-zoom' have now become de facto interactions. Other steps to increase the interaction library, such as the use of multiple fingers simultaneously, have been adopted in niche applications, but have not found widespread adoption amongst users. As an alternative approach to the number of fingers as a parameter to extend the touchscreen vocabulary, the identification of which finger, from the 10 the user possesses, offers potential (See Figure 15).

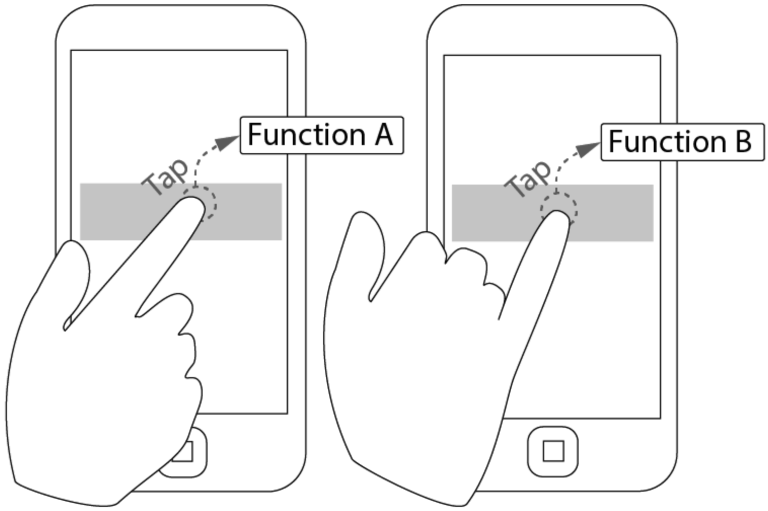


**Fig. 15.** Finger specific input concept. Each finger of the user's hand can trigger a different functionality when touching the screen. (From Publication III).

Whilst the functionality to identify the finger that is touching the screen is not currently available in commercial touchscreens, there are several promising technical approaches that will no doubt bring this functionality at some point in the future, e.g. (Benko et al., 2009; Sugiura & Koseki, 1998). Publication III explores the concept of finger specific interaction from a user experience viewpoint, and as a first step quantifies how well users are actually able to perform simple touchscreen interactions with each of their fingers. In a user study with 37 participants it was established that, although users were able to interact with all of the fingers on their dominant hand, there were differences in comfort, accuracy and speed between fingers. The study also identified a dependency on the location of the target on the device screen with the ability to interact with different fingers. For example, interaction with targets in the top left of the screen with finger 4 (the little finger), was problematic.

After having established the usability of interacting with each of the fingers, follow up studies focused on use cases for the approach. Two studies were made, the first utilising a Wizard-of-Oz methodology (Salber & Coutaz, 1993), where a moderator manually identified the finger the user was interacting with, whilst the second used an infra-red camera to identify the interacting finger. Prototypes of two common mobile phone applications, phonebook and gallery, were created including finger specific interaction. The functionality attached to each finger is detailed in Table 1.

**Table 2.** Finger specific functions of the prototype phonebook and gallery applications (see Publication III)

| Finger | Phonebook | Gallery |
|---|---|---|
| Thumb | Call tapped contact | Show sharing context menu |
| Finger 1 | Open tapped contacts contact card | Edit image |
| Finger 2 | Open "Open apps" pop-up | Open "Open apps" pop-up |
| Finger 3 | Delete the tapped contact | Delete the tapped image |
| Finger 4 | Open global help view | Open global help view |

Overall the finger specific shortcuts were well received, with an example user commenting, *"This is faster to use than long press, which is often used for this kind of open apps list"*. However, issues related to memorability and risk of accidental activation were raised. In particular, the attachment of delete functionality to finger 3 (ring finger) was considered risky.

### 4.3.3 Touchscreen Lock Mechanism

Touchscreen based devices such as smartphones and tablets have nowadays become our personal assistants, holding a large amount of private information. Thus, a critical requirement for such devices is a secure locking mechanism to prevent unauthorised access to the information. However, this requirement needs to be balanced with the user's need to easily access the device, to which any unlocking process is an annoying precursor. Studies have shown that the mean number of times a user unlocks their smartphone is 47.8 times per day (Harbach et al., 2014).

One of the most popular lock mechanisms, primarily due to its ease of use, is the grid pattern lock mechanism, available as default on Android touchscreen devices. The mechanism is based on a 3x3 grid of nodes over which a single stroke gesture is made. In the baseline lock mechanism, each node can be selected only once, giving a maximum pattern length of 9 nodes. Prior work has shown that the pattern lock mechanism is vulnerable to attack due to 1) the actual lock patterns used by individuals are limited, e.g. many codes start at the top left node (Andriotis et al. 2014), and 2) Physical residues or smudges on the screen can make the lock pattern visible (Aviv et al. 2010).

To address the security issues Publication VII introduces a concept that extends the pattern lock mechanism by enabling each node in a 3x3 grid to be used multiple times, including the repetition of a node directly after it has been used (Figure 16). This increases the resilience of the lock mechanism both by increasing the code space and by creating smudge patterns that are ambiguous. The concept was implemented and evaluated in a laboratory user test (n = 36). The test participants found the usability of the proposed concept to be equal to that of the baseline pattern lock mechanism, but considered it more secure. The solution is fully backwards compatible with the current baseline pattern lock mechanism, hence enabling easy adoption while providing higher security at a comparable level of usability

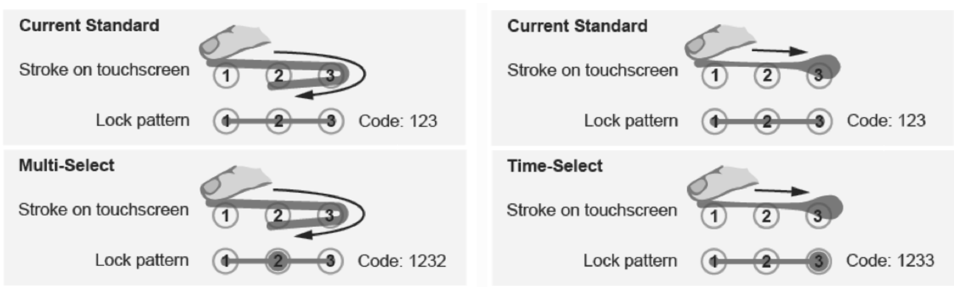


**Fig. 16.** Pair-wise comparison of the proposed lock mechanisms to the standard pattern lock. In each illustration, the unlock action starts at node "1" and ends at the large red dot. Left pair: In the multi- select condition, the "2" is added to the pattern by moving over a previously selected node. Right pair: In the time-select condition, a second "3" is added to the pattern. 'Long-press' allows the current node to be reselected and added to the pattern. (From Publication VII).

Patent P1 also addresses issues related to touchscreen locking, proposing the introduction of a partial lock mode, aiming to reduce the number of occasions on which the user needs to unlock the touchscreen. In the partial lock mode, certain limited functionality is made available to the user via the touchscreen without the need to unlock the device. Example use cases are, music controls whilst listening to music, map panning whilst in a navigation application and web browsing. Different approaches to the partial lock are proposed, including defining a restricted area of the screen for interaction, or allowing only certain gestures whilst the device is locked. The concept is illustrated in Figure 17.

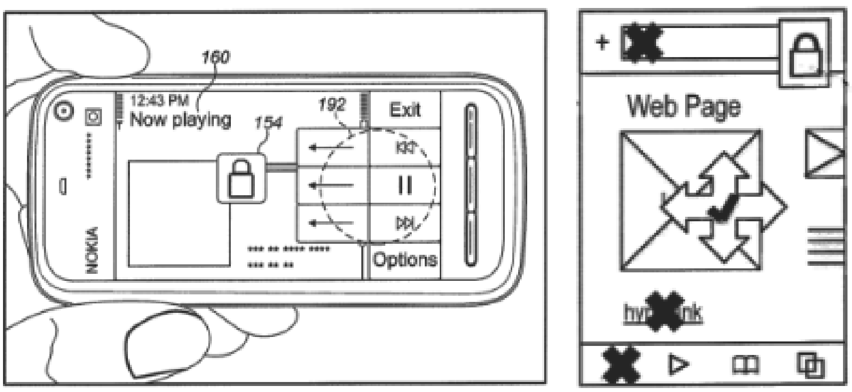


**Fig. 17.** Partial lock mechanism. Left: Music player controls are operable with a sliding gesture whilst the screen is in partially locked mode. Right: in partial lock mode the web page may be panned, but all other functionality is locked. (From Patent P1),

### 4.3.4 Touchscreen Automotive Dashboard UI

As noted earlier, touchscreen based interfaces are penetrating to contexts which have previously been the domain of purpose designed physical interfaces, the car dashboard is one such domain, and thus an interesting area for study. Publication IV presents a comparative user study of 3 alternative interaction methods for a touchscreen car dashboard; normal touch, multi-finger interaction and finger-specific interaction. The latter as earlier described and detailed in publication III. Traditional physical car dashboard controls, such as heating, radio and lighting controls are usable to some degree without the driver removing their gaze from the road in front of them. A target of the concept was to create a touchscreen interface that would require a minimum level of visual attention to operate it. Figure 18 presents an overview of the interaction modes and screenshots of the dashboard UI.

In a user evaluation of the interaction techniques (n=15) in an in-car context, users subjectively considered that both alternative interaction techniques required less visual attention than normal touchscreen interaction. However, no significant differences in the measured glancing times between the modes was found. Here, the variance between participants was smallest in the finger-specific mode, indicating more homogenous user performance. In the case of multiple-finger gestures, more than a third of users complained of difficulties in gestures requiring 4 fingers - indicative of a limitation in this approach.

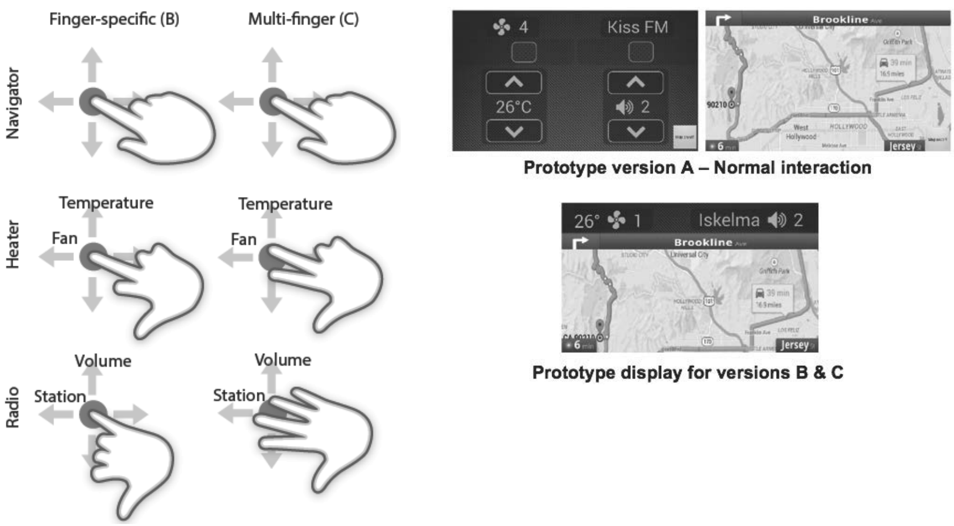


**Fig. 18.** Touchscreen car dashboard concept. Left: functions attached to finger-specific and multi-finger interaction. Right: Example screenshots from the prototype presenting heater, radio and navigator functions. (From Publication IV).

## 4.4 Extending Visual Output

The visual output aspect of touchscreens is perhaps more fundamental to their being than input aspect, as many touchscreen devices evolved from devices with non-interactive screens plus separate input mechanisms – before they were touchscreens they were displays. In this section the author's work on two approaches to extending the visualization possibilities of mobile touchscreen devices is presented, stereoscopic 3D (S3D) displays and handheld projection. This section concludes with a case study where a touchscreen is integrated into a handbag, creating a wearable touchscreen public display.

### 4.4.1 3D Visualization

**Stereoscopic Touchscreens**

Human vision is three-dimensional (3D). We are able to understand the depth dimension of what we see through the interpretation of various depth cues, such as occlusion, relative object size and motion parallax. In addition to the aforementioned monocular depth cues, the stereoscopic human vision system provides additional information in the form of binocular disparity and convergence. By combining all these depth cues, the human brain is able to present us with a 3D representation of the world. The relative strengths of each depth cue and their operational distance ranges have been presented by Cutting and Vishton, (1995). Whilst occlusion is the strongest depth cue and functions over the entire distance range, binocular disparity, which is relevant only in the range 0 - 2m. As this range is a typical eyes-to-screen distance for mobile device use, the inclusion of stereoscopy is important to create a realistic perception of depth on such devices. Thus, the use of stereoscopic displays presents a logical direction in which the visual aspects of mobile touchscreen devices may evolve.

Stereoscopic 3D (S3D) mobile devices are already mass-market products, and the penetration of such devices is growing in numbers. Autostereoscopic mobile 3D displays, where no special glasses (or similar devices) are needed to experience the 3D effect, can be found in 3D cameras (e.g. FinePix REAL 3D W3), mobile phones (e.g. LG Optimus 3D), and portable game consoles (e.g. Nintendo 3DS).

Following a similar approach to Publication II, which studied 2D touchscreen usage accuracy, Publication V investigates the accuracy with which users can interact with stereoscopic touchscreens, in both tabletop and mobile device form factors. In the scope of this thesis we focus on the later, and report on interaction with a mobile autostereoscopic touchscreen, both whilst static and walking. A user study with 27 participants was performed to assess how mobile interaction, i.e. whilst walking, with mobile S3D devices, differs from interaction with 2D mobile touchscreens.

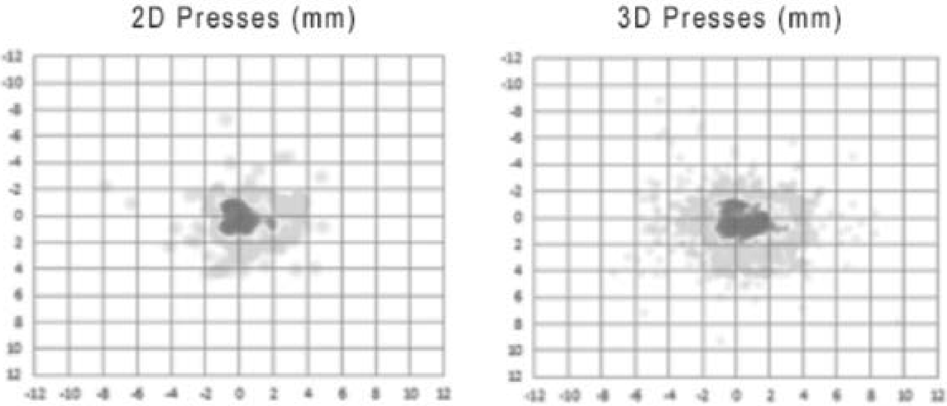


**Fig. 19.** Heatmap of press coordinates relative to center of visual target for 2D and 3D display modes. Note the wider spread in the 3D case. (From Publication V).

The study setup consisted of an S3D capable mobile phone on which visual targets were displayed in both 2D and 3D modes. Test participants were then required to tap the targets as accurately as possible in both modes, whilst static and walking. The findings indicated that the 3D mode resulted in a wider spread of touch points around the visual target, i.e. reduced accuracy (see Figure 19). Additionally, in both 2D and 3D modes, walking also resulted in reduced accuracy. Thus a mobile S3D touchscreen device will require larger on-screen touch target sizes than a comparable 2D device. The relative touch target sizes required for each mode are presented in Figure 20. The minimum sizes for 95% presses on target was found to be 8.4mm x 9.2mm (width x height) for 2D vs. 12.0mm x 10.4mm for 3D. Although these values are based on the test device used, it is expected that they should be generally applicable to other similar S3D devices.

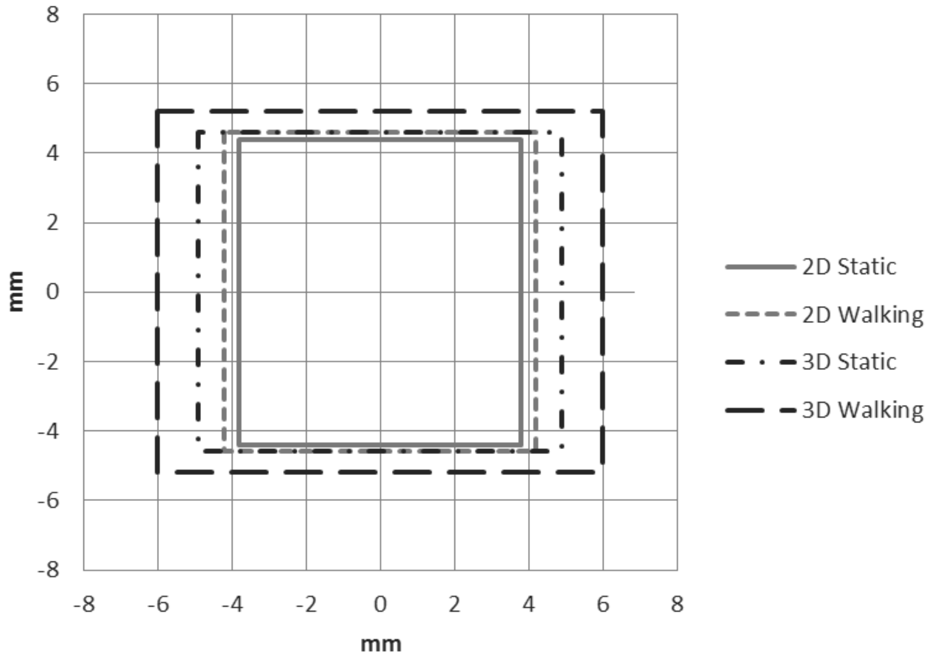


**Fig. 20.** Touch target sizes for 95% of presses on target. Comparing 2D and 3D display modes in static and walking usage. (From Publication V)

In addition to issues of touch accuracy with S3D mobile device, the author has also investigated issues related to depth perception with such devices, concluding that using such devices whilst walking deteriorates the user's perception of depth (Colley et al., 2013).

***Interaction with 3D Content on Touchscreens***

One of the main advantages of touchscreens is their propensity for direct interaction, i.e. objects displayed on the screen can be directly touched and manipulated like physical objects. However, this also sets limitations that the displayed objects, or visible areas of objects, need to be sufficiently large that they can be touched with the users' finger (assuming finger based interaction). In the case of 3D content, it is often the case that objects on the screen will be occluded, or partly occluded by other objects, and thus not touchable. Patent P5, presents a solution to this whereby the touchable area of objects is monitored by the system and the display parameters, e.g. view point, are adjusted such that the maximum number of displayed objects can be directly interacted with, without the need for manual adjustment.

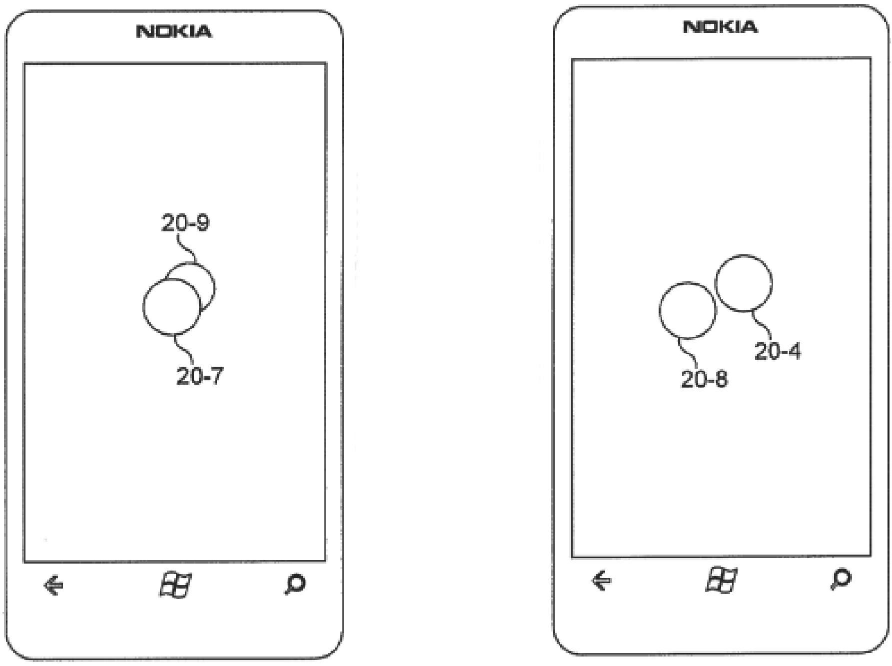


**Fig. 21.** Automatically adjusting viewpoint in a 3D scene to enable objects to be touched. Left, before adjustment. Right, after adjustment. (From Patent P5).

### 4.4.2 Integrating Handheld Projection

Although there has been a gradual increase in the screen size of smartphones over recent years, with sizes of 5” diagonal now being commonplace, the size of mobile handheld device displays is fundamentally limited by the practical restrictions of the form factor. For example, it should be possible to operate it whilst walking, it can be stored in a coat pocket etc. However, some use cases may benefit from the possibility for a larger display, or a display that is somehow remote from the handheld device itself, e.g. for viewing by a group. Thus, the incorporation of mobile projection with a touchscreen mobile device offers an interesting direction to extend the visualisation space of mobile touchscreen devices.

As described in the literature study section of this thesis, much prior work has been made on the area of handheld projection. Publication VI studies a particular application of creating a virtual window using a touchscreen device equipped with a picoprojector. The second study in the work presents a handheld CAVE prototype that used the spotlight metaphor to reveal parts of a virtual environment, visualized as a sphere around the user. The system aimed to create the illusion of the user standing in the middle of a hidden, virtual environment, which the user can access by pointing a projector phone (a Samsung Galaxy Beam Android phone) to an arbitrary direction (360 degrees in 3D) around themselves (Figure 22).

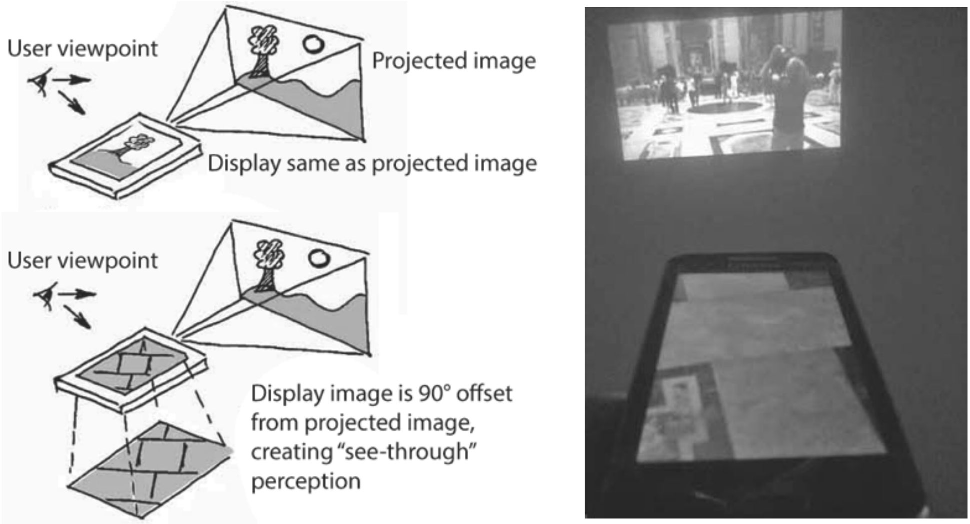


**Fig. 22.** Extending touchscreen device visualisation with picoprojection. Left: as well as duplicating the mobile device's screen the projected image and image on the screen may be offset by 90°. Right: Example showing a combination of viewpoints, with the device screen showing the floor of the location being presented. (From Publication VI).

In a user test (n = 23), different combinations of content shown on the device screen and projected display were evaluated. Overall, test participants found the concept of the projected CAVE interesting, the dual display approach was liked, however no significant preference for between the dual display modes was found. Findings were, e.g., that the full spatial scale should be utilized in 3D browsing, i.e. also pointing to the ceiling and floor should be supported and that the level of horizon should be kept horizontal when browsing in with the projector.

### 4.4.3 Smart Handbag as a Public Display

Whilst handheld smartphones and tablets have become the predominant format for mobile computing devices, other form factors e.g. wearables are also available. Handbags as physical items can be positioned on the periphery of wearable computing. They are accessories, which are strictly speaking not wearables, however they are often considered as part of a clothing outfit and coordinated with clothes. Thus an interesting research direction is to look at the integration of a touchscreen into a handbag, creating a portable public display.

**Fig. 23.** The mobile touchscreen output space extended by integration of a touchscreen to a handbag. (From Publication VIII).

Publication VIII describes a case study where a prototype smart handbag was developed and evaluated in a user study (Figure 23). The handbag demonstrated several features, including matching the display to the wearers outfit and acting as a public information display, e.g. displaying a motto selected by the user. Additionally, the prototype also illustrated a feature which allowed the user to see objects contained within the handbag and interact with some of them via the handbag's touchscreen. For example, when a message was received on a mobile phone contained inside the handbag, the user could read the message without removing the mobile phone from the handbag.

Overall the smart handbag concept captivated the interest of the majority of test participants. This was apparent not only in the positive adjectives used to describe the presented concepts, but also in the wealth of ideas that the participants provided for iterating the concepts. This high level of interest also highlights the special status of the handbag for many users, beyond its practical role of a functional accessory to simply carry personal items. The possibility to interact with items inside the handbag without having to remove them was felt to be both efficient and to reduce the risk of theft of removed items. Although we presented this concept largely in the context of simple interaction with a mobile phone, study participants proposed extending this scope, particularly towards issues related to calendar, notifications and schedule management. Here, it may be interesting to draw parallels with smartphone usage in the car context, where a 'car mode' provides a context appropriate view to the smartphones functionality, viewed on a display embedded in the car's dashboard. Thus a 'handbag mode' may be appropriate.

## 4.5 Extending Haptic Feedback

Feedback is a key element of interaction, providing confirmatory output for physical input actions. Whilst touchscreen interaction enables huge flexibility for the interface to be cost efficiently optimized to meet the requirements of each use case, it loses many of the benefits of a mechanical control based interface. Interfaces with physical push buttons, mechanical knobs that can be rotated and sliders that can be physically moved, provide a far more tangible experience than touchscreen UIs, and as a consequence reduce the requirement on the visual sense for operation. In addition to tactile feedback, provided by touching, many mechanical interfaces also provide kinaesthetic feedback to the user, requiring the user's muscles to push or pull during operation.

As described in detail in the related work section of this thesis, many approaches such as the use of vibration and electrostatic based feedback have been explored to address this limitation. As alternatives to these approaches, the author has investigated the use of static physical overlays and touchscreens that can physically morph, as methods of improving the feedback provided by touchscreen interaction.

### 4.5.1 Guided Touchscreen Interaction

With the aim of combining some the benefits of mechanical interaction with those of touchscreen interaction, Publication I presents a concept where touchscreen interaction is guided by an overlaid transparent acrylic sheet that enables only interaction with areas of the screen where holes are cut out in the overlay, i.e. 'guided touch' (Figure 24, left). This potentially provides benefits such as giving natural passive haptic feedback, reducing erroneous screen touches and improving eyes-free usage.

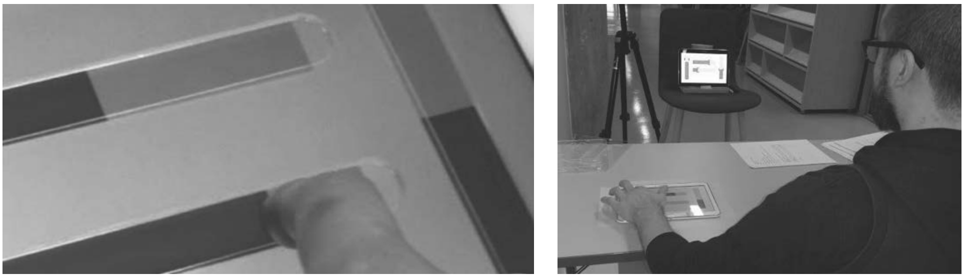

**Fig. 24.** The eyes-free use of the touchscreen enhanced by the addition of a Perspex guiding layer (from Publication P1).

In a user test (n = 20) participants were required to split their attention between a touchscreen controller with slider controls, and a distant output display screen (Figure 24, right). No difference was found in the total interaction time between the baseline normal touchscreen interaction and guided touch interaction. However, in the guided touch solution, the user's finger was in contact with the touchscreen for a significantly longer time than in the normal touchscreen case. The guided touch solution was considered easier to use when completing the test task. Participants commented that the guided touch solution improved eyes-free usage, but also identified limitations in the approach. Other shapes of guide overlay such as circles, zig-zags and toothed tracks were considered as suitable for specific interaction tasks, typically analogous with real-world objects or interactions, e.g. circular interaction for a speed control.

Such guided touch solutions may find application e.g. in use cases where the functionalities provided by a touchscreen UI are fixed, or change in a modal fashion such that overlays could be changed for each use case. In particular, use cases where eyes-free usage is important, such as the control panels for industrial or agricultural machinery, could benefit from this approach.

### 4.5.2 Other Approaches to Extend Touchscreen Feedback

Patents P2 and P3 are patent applications by the author that present novel approaches to improving touchscreen feedback.

#### *Dynamic screen topology*

In patent P2, the flat touchscreen is augmented with physical projections, indentations or changes in surface texture which can be felt by a user touching the screen. This is achieved through the inclusion of an electroactive polymer (EAP) layer underneath a flexible screen surface layer. The electroactive polymer is a material which changes shape when a voltage is applied to it. By configuring EAP elements e.g. in a grid pattern, localized changes in topology can be created, i.e. each EAP element is raised or lowered with respect to the other elements (Figure 25, left). The work presents several concepts for how the physical topology changes may be integrated with the visual UI element displayed on the screen, for example raising a button, adding a marker on an item in a list, or creating a physical border between areas of the touchscreen. Here, similarities with the previously presented guided touchscreen concept should be noted. In this approach, physical topology based touch guides may be created dynamically.

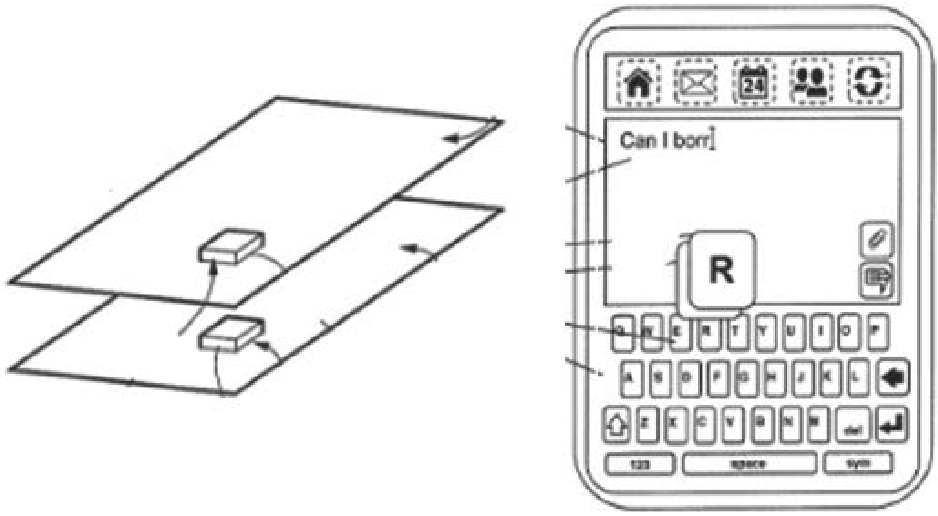


**Fig. 25.** Left to right: Touchscreen surface topology created though the inclusion of an electrostatic polymer layer in the screen (Patent P2). A second tap on the 'R' key within a short time window creates different feedback from the initial press (Patent P3).

***Sequential Touches***

Due to the lack of tactile feedback from touchscreens, interactions that require repeated finger touches to the screen are particularly problematic. For example, when typing words on an onscreen keyboard that include repeated characters, e.g. "Hello", or other operations that require multiple tap interactions on the screen. The visual feedback typically provided by touchscreen UIs is not rapid enough, or cannot be perceived rapidly enough by the user, to provide positive confirmation that the interaction is as intended. Patent P3 proposes a solution whereby touchscreen interactions in the same physical location within a short time window are identified and specific confirmative feedback is provided to the user. This feedback may be visual, e.g. when typing text, the character pop-up for the second character is displayed separately to the pop-up for the initial character (Figure 25, right). Alternatively, if the system utilises vibra based haptic feedback, a different vibration pattern can be delivered for the second press within the time window. This approach differs from that typically used in touchscreen haptics solutions, where the aim is to recreate haptic experiences from physical controllers.

# 5 Discussion

This thesis addressed the research question:

- What are the ways in which interaction with mobile touchscreen devices may be extended?

By addressing this question the work aimed to explore potential evolutionary additions to the current de facto standard human computer interface, the touchscreen. As described in the related work section, the possible scope of the topic is huge. Through the presented design space, the author has attempted to provide some structure to the space. Although noting that this can in no way be fully comprehensive, it is believed that all potential enhancements in the domain may be somehow mapped to the presented space. Here, the limitation of the work, as set out in the introduction should be noted, that it restricts itself to only visual and tactile senses.

In answer to the research question, a variety of solutions within the breadth of the design space were investigated. Firstly, solutions aiming to improve the basic interaction experience with mobile touchscreens were presented i.e., improving interaction accuracy and reducing accidental interaction. The work then progressed to explore concepts that extracted more granularity of information from interaction by using the shape of the finger's contact area or attaching particular functionality to individual fingers. Solutions combining touchscreen interaction with 3D, stereoscopic and projected displays were then explored. A solution guiding touchscreen interaction with a physical overlay layer and concepts in the area of morphing screens and sequential touches were studied in the area of haptic feedback. In addition, case studies in the areas of a touchscreen pattern lock mechanism, an automotive dashboard UI, and a handbag with an integrated touchscreen, explored more application specific approaches to the topic.

Clearly the research question is extremely broad, and whilst it would be impossible to address it completely in the scope of this work, the work has presented concepts across the full range of the topic. As a consequence, novel concepts and new data have been created and several concept areas have been identified as lucrative for further research.

## 5.1 Main Findings

The work has provided fundamental new data, in several areas, for example the quantification of the parameters of an intentional tap interaction (Publication II), quantifying the performance of each of the 5 digits in interacting with a touchscreen (Publication III) and the reduction in touch accuracy induced by stereoscopic mode on a small display (Publication V). Such data forms a valuable reference for the research community.

As well as quantitative findings the work has exposed many aspects related to the user experience of interacting with current touchscreens and enhancements to them. The work on the smart handbag was particularly notable in this respect (Publication VIII), highlighting how intensely personal handbags are to their users. The work reporting on finger specific touchscreen usage (Publications III and IV) and picoprojection (Publication VI), focused primarily on exploring users' subjective perceptions of the solutions, in both cases finding the directions interesting, but also exposing practical problems to be solved.

## 5.2 Shorter and Longer Term Possibilities

Of the specific areas that the author selected to explore in detail, several have presented novel concepts that expand the current state of knowledge for touchscreen interaction, and create stepping-stones for subsequent researchers and designers. The work has presented concepts at a mixture of current commercialisation feasibility levels. Particularly the works on touchscreen locking mechanisms, improving the accuracy of touches and rejection of unintentional touches are such that they could be directly implemented to current mass market smartphones and deliver small, but important experience improvements to huge numbers of users. Although elements of the unintentional touch filtering were implemented under the author's guidance to Nokia touchscreen smartphones, these have been unavailable for several years. However, the author has recently noticed related features in current smartphone models e.g. the press action on the 'end' button whilst in a phone call on some Android smartphones is cancelled after 2 seconds, thus preventing ear-touch based call termination. Accidentally hanging up whilst in a phone call is a critical usability error from which only a clumsy (and often embarrassing) recovery mechanism exists. Thus, small improvements in this area deliver valuable user experience gains.

The work has also defined, small but valuable user experience increments in the area of touchscreen security (Publications VII and Patent P1), focusing on the creation of practically usable mechanisms that suit the use context, rather than high security at the expense of usability. Functionality similar to the partial lock mechanism of Patent P1 (filed in 2011) can be found in current leading smartphones which enable access e.g. to music player controls from the touchscreen in locked state.

In contrast to the concepts that are readily implementable, several of the other concepts presented are rather more future oriented. Here the work on finger specific input (Publications III and IV) and dynamic physically touchscreen topology (Publication I and P2) are perhaps the main examples in this respect. Although technical solutions for both currently exist, their readiness level is currently insufficient for deployment in mass market consumer products. Somewhat similarly, the stereoscopic touchscreens presented in Publication V and picoprojectors of Publication VI have not yet achieved true mass market penetration, being only available in niche products. The presented work on these topics aims to prepare the way for technology readiness, by identifying user experience challenges and potentials in advance.

## 5.3 Methodological Notes

A main approach of the work has been to create functional prototypes and evaluate them in users' hands, in fact this has been the case in all 8 papers carried out as part of this thesis. In particular, the value of collecting both quantitative and qualitative data has been a mainstay of many of the presented studies. This is important in the context of emerging technologies as the solutions will potentially develop towards consumer products, where both usability and hedonic aspects play important roles.

The use of the Wizard-of-Oz method (Salber & Coutaz, 1993) deserves special mention as it was utilised in 3 of the 8 works (publications III, IV and VII). In each case, by using a human operator to simulate part of the function of a computer system, the resulting user experience was closer to that expected of a future final product, and thus a more valuable source of user feedback than a poorly functional autonomous prototype. Overall the Wizard-of-Oz method has shown itself to be a useful tool when user experience rather than technical proof of concept is the driver. Related to this, the author plans to release a version of the Wizard-of-Oz app utilized in Publication VII on the Google Play store. The app enables researchers to load their own screen images to one android device, and remotely control which image is displayed from a second android device. Image layering, such that, if required, only some elements in the screen image can be switched is also supported.

## 5.4 Personal Reflections and Future Work

The author has been involved in the area of touchscreen interaction research for many years, from early works in Nokia in 2004 to more recent works at the University of Lapland. As an interesting observation, the author notes the large disconnect between promising research work and features that have found their way into mass market consumer products. Nevertheless, touchscreen interaction has made huge advances over recent years, and nowadays even small improvements and additions can affect the daily interaction of hundreds of millions of users.

This work offers several potential tracks for future work. As noted in the introduction to this work, part of its goal is primarily to provide interim advances which serve as starting points for further research in the area, that in turn leads to work towards productized innovation. Two highly diverse directions of the author's work appear to present the most lucrative items for future work, finger specific interaction and the smart handbag. In the former case, various technical solutions to enable individual finger sensing are approaching commercial status, whilst at the same time the demand for increasing the touchscreen input space with usable additions is constantly increasing. Suitable further work in this area would be e.g. exploring usage in different contexts than the current car dashboard case and integrating functional technology. The smart handbag presents opportunity for future study predominantly driven by the huge enthusiasm and ideas provided by test participants in the initial study. From the author's personal view point the topic is interesting in its combination of design and technology. Here, next steps would involve the production of real functional smart handbag prototypes that are practically usable in a long term study.

# 6 Conclusion

Touchscreens have become a de facto interface for mobile devices, and are penetrating further beyond their core application domain of smartphones. The design space presented in this work enables solutions for extending touchscreen interaction to be mapped. This thesis presents and evaluates several solutions within the design space, each with potential to extend the interaction in some dimension. This work presents studies on the following areas:

- Improving interaction reliability, addressing both true and false positives.
- Extending the input vocabulary by using the finger contact shape and by assigning functionality to specific fingers.
- Exploring touchscreen interaction with 3D content, stereoscopic touchscreens, and handheld projection.
- Investigating the effect of placing a physical guide layer on top of the touchscreen surface.
- Case studies on enhanced touchscreen solutions for touchscreen unlocking, an automotive dashboard UI and a touchscreen integrated in to a handbag.

As a conclusion, the key findings from the studies are summarised in the following.

The basic user experience of touchscreen interaction may be improved through the application of a touch filtering layer, classifying touches e.g. by time the finger is in contact with the screen. Such a functionality is able to reject 79.6% of unintentional touches, whilst having minimal effect on the intentional touch performance, reducing it by 0.8%. Locking the touchscreen is a critical part of interaction with a touchscreen device. The extensions proposed to the pattern grid lock mechanism, e.g. enabling a node in the pattern to be selected multiple times, provide an improvement in perceived and actual performance without decreasing usability.

Extending the touchscreen input vocabulary through identifying the specific finger touching the screen has been demonstrated as a valuable approach. In particular, a potential benefit is improvement in eyes-free interaction with the touchscreen. Also aiming to improve eyes-free usage, the placement of a transparent Perspex guiding layer on top of the touchscreen resulted in users being able to move between touchscreen control elements more rapidly, whilst focusing on a distant task.

Two methods to extend the output space of touchscreens beyond the standard two-dimensional screen are stereoscopic 3D (S3D) displays and picoprojection, integrated into a touchscreen device. Although both approaches were considered to provide interesting enhancement, both bring usability challenges. For example, in the case of S3D the minimum sizes for touchscreen targets increased from 8.4mm x 9.2mm (width x height) for 2D to 12.0mm x 10.4mm for 3D

This work draws together solutions from the broad area of mobile touchscreen interaction. These offer the potential to extend the current touchscreen interaction in the domains of manual input, haptic feedback and visual output. Fruitful directions for future research are identified and information is provided for future researchers addressing those topics.

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# Original Publications

[Original publications are not included
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