# In Your Face! – Designing Future Interaction Models for Internet of Things and Augmented Reality

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# In Your Face!

## Designing Future Interaction Models for Internet of Things and Augmented Reality

**GÜNTER ALCE**
**DEPARTMENT OF DESIGN SCIENCES | FACULTY OF ENGINEERING | LUND UNIVERSITY**

More and more devices are being connected to the Internet but how should we discover and directly interact with all of them in an intuitive and comfortable manner? Up until now, smartphones have shown potential for managing the Internet of Things (IoT) environments, but we cannot rely on that technology. Wearables, on the other hand, are becoming more mature and are available in many different form factors. It is speculated that combining wearables with augmented reality (AR), which has the ability to merge the real world with the virtual, is more suitable.

The aim of the research presented in this thesis was to develop and explore three tools that can be used for prototyping AR and IoT interaction and to introduce four interaction models for controlling IoT devices.

**GÜNTER ALCE** started to work at Ericsson as a software engineer after his Master of Electrical Engineering in 2000. After having worked with low-level software, he moved on to Sony Ericsson working with user interfaces. Next, he started to work at the technology office at Sony as Senior Engineer. Eventually, Günter looked for new challenges and decided to do his Ph.D. at the Department of Design sciences at Lund University. His research is focused on Augmented Reality interaction for the glass form-factor.

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# In Your Face!

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Günter Alce

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UNIVERSITY

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**Abstract**

It is estimated that the number of devices connected to the Internet will be 50 billion by 2020. How should a not-so-tech-savvy end user be able to discover and directly interact with a myriad of connected things in an intuitive and comfortable manner? Up until now, smartphones have shown potential for managing the Internet of Things (IoT) environments, but we cannot rely on that technology. Wearable technology devices are maturing and are available in many different form factors including head-worn displays (HWDs), smartwatches and wristbands. They enable access to information at a glance. They are intended to always be “on”, to always be acting and to always be sensing the surrounding environment in order to offer a better interface to the real world. A technology suitable for these kind of user interfaces is augmented reality (AR) due to its ability to merge the real with the virtual. However, prototyping AR user interfaces to discover and control connected things can be difficult and costly because it involves a number of different devices and systems with varying levels of technological readiness.

The aim of the research presented in this thesis was to develop and explore three tools that can be used for prototyping AR and IoT interaction and to introduce four interaction models for controlling IoT devices. One of the tools is based on real-world Wizard of Oz (WOZ) prototyping method, which let a human operate undeveloped components of a technical system and the other two are built on virtual reality (VR) -based prototyping for an IoT environment. The interaction models were developed for different form factors. One is based on a smartwatch form factor and an interaction model called *UbiCompass*, and three are based on HWD form factor and interaction models called *Floating Icons*, *World in Miniature* and *Floating Menu*, respectively.

Overall, the research presented in this thesis found the three prototyping tools – WozARd, IVAR, and VRUbi – to be useful for prototyping AR and IoT interaction. One important takeaway for organizations that develop IoT systems or services is to use VR to simulate different scenarios and interactions. The two VR-based prototyping tools are suitable for simulations of more complex scenarios, since registration and tracking can be easily simulated, while WozARd is suitable for prototyping simple AR user interfaces.

Overall, the interaction models presented utilize two form factors – smartwatch and HWD – both of which did well during the experiments. They both focus on three aspects: discovering connected devices; selecting and controlling connected devices; and that the user not needing to start an application. An example of the later is that the user interface should just appear when a person enters a smart office.

Key words
Internet of Things, Augmented Reality, Wearables, Virtual Reality, Prototyping, User interface

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*"Life's not about how hard of a hit you can give... it's about how many you can take, and still keep moving forward."*
*Sylvester Stallone, in Rocky Balboa.*

*"Success consists of going from failure to failure without loss of enthusiasm."*
*Winston Churchill.*

*"By silence, I hear other men's imperfections and conceal my own."*
*Zeno of Elea*

*"Peace at home is peace in the country. Peace in the country is peace in the world."*
*Mustafa Kemal Atatürk*

*"Alla goda bullar börjar med en smet."*
*Mattias Wallergård*

# Table of Contents

# Acknowledgement

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Finally, my two lovely sons Berk and Beran and my lovely wife Beyhan for supporting and listening to all the challenges that I have faced during this exciting adventure. Sizi çok seviyorum.

# Abstract

It is estimated that the number of devices connected to the Internet will be 50 billion by 2020. How should a not-so-tech-savvy end user be able to discover and directly interact with a myriad of connected things in an intuitive and comfortable manner? Up until now, smartphones have shown potential for managing the Internet of Things (IoT) environments, but we cannot rely on that technology. Wearable technology devices are maturing and are available in many different form factors including head-worn displays (HWDs), smartwatches and wristbands. They enable access to information at a glance. They are intended to always be "on", to always be acting and to always be sensing the surrounding environment in order to offer a better interface to the real world. A technology suitable for these kind of user interfaces is augmented reality (AR) due to its ability to merge the real with the virtual. However, prototyping AR user interfaces to discover and control connected things can be difficult and costly because it involves a number of different devices and systems with varying levels of technological readiness.

The aim of the research presented in this thesis was to develop and explore three tools that can be used for prototyping AR and IoT interaction and to introduce four interaction models for controlling IoT devices. One of the tools is based on real-world Wizard of Oz (WOZ) prototyping method, which lets a human to operate undeveloped components of a technical system, and the other two are built on virtual reality (VR) - based prototyping for an IoT environment. The interaction models were developed for different form factors. One is based on a smartwatch form factor and an interaction model called *UbiCompass*, and three are based on HWD form factor and interaction models called *Floating Icons*, *World in Miniature* and *Floating Menu*, respectively.

The thesis is based on the five attached papers.

Paper 1 presents a WOZ prototyping tool called WozARd and the set of features it offers. The WozARd device allows the test leader to control the visual, tactile and auditive output that is presented to the test participant. The study described in Paper 1 is an initial investigation of the capability of the real-world prototyping method with WOZ to simulate a believable illusion of a real working AR city tour. A user study was carried out by collecting and analyzing qualitative and quantitative data from 21 participants who performed the AR city tour using the WozARd with an HWD and smartwatch. The data analysis focused on seven categories that can have a potential impact on how the WozARd method is perceived by participants: precision, relevance,

responsiveness, technical stability, visual fidelity, general user experience, and human operator performance. Overall, the results seem to indicate that the participants perceived the simulated AR city tour as a relatively realistic experience despite a certain degree of technical instability and human operator mistakes.

Paper 2 presents a proposed VR-based prototyping tool called IVAR (Immersive Virtual AR) for prototyping wearable AR and IoT interaction in a virtual environment (VE). IVAR was developed in an iterative design process that resulted in a testable setup in terms of hardware and software. Additionally, a basic pilot experiment with 24 participants was conducted to explore what it means to collect quantitative and qualitative data with the proposed prototyping tool. The main contribution is that IVAR shows potential to become a useful wearable AR and IoT prototyping tool, but that several challenges remain before meaningful data can be produced in controlled experiments. In particular, tracking technology needs to improve, both with regards to intrusiveness and precision.

Paper 3 presents a proposed VR-based prototyping tool, using VR technology based on room-scale tracking to prototype IoT interaction. It is built on the same idea as in Paper 2. We refer to the prototyping tool as VRUbi. Three IoT interaction concepts were compared in a controlled experiment with 21 test persons for evaluation and comparison. Some statistically significant differences and subjective preferences could be observed in the quantitative and qualitative data, respectively. The main contribution of this paper is to elucidate knowledge about the method of using VR as a prototyping tool to explore IoT interaction.

Paper 4 presents a novel IoT interaction concept called UbiCompass. A functional, smartwatch face prototype of the UbiCompass was developed and integrated with an existing smart home system. It was then compared to a traditional smart home mobile application in a controlled experiment. In total 36 participants were recruited for the experiment. The results showed statistically significant differences in favor of the proposed concept, which highlights the potential the UbiCompass has as an IoT interaction concept.

Paper 5 presents three basic IoT interaction models, with a focus on the aspects of discovering and selecting devices, implemented for Microsoft HoloLens. The intention was to compare the models in an experimental study with 20 participants. They were split into two groups: one with low device density and one with high device density. Each group had to solve the same task using each of the three interaction models. The results showed that with just a few devices to interact with, the participants' interactions did not differ significantly. However, with many devices to engage with, the World in Miniature model stood out as especially demanding and time-consuming. There was also high variability in the models that were preferred by the participants, possibly implying that a combination of the three proposed models is desired in a fully developed AR system for managing IoT devices.

Overall, the research presented in this thesis found the three prototyping tools – WozARd, IVAR, and VRUbi – to be useful for prototyping AR and IoT interaction. One important takeaway for organizations that develop IoT systems or services is to use VR to simulate different scenarios and interactions. The two VR-based prototyping tools are suitable for simulations of more complex scenarios, since registration and tracking can be easily simulated, while WozARd is suitable for prototyping simple AR user interfaces.

Overall, the interaction models presented utilize two form factors – smartwatch and HWD – both of which did well during the experiments. They both focus on three aspects: discovering connected devices; selecting and controlling connected devices; and that the user not needing to start an application. An example of the later is that the user interface should just appear when a person enters a smart office.

# Sammanfattning

Det beräknas att antalet enheter som är anslutna till Internet kommer att vara 50 miljarder år 2020. Hur skall en relativt teknikovan slutanvändare kunna upptäcka och direkt interagera med en mängd uppkopplade saker på ett intuitivt och bekvämt sätt? Hittills har smarta mobiler visat potential för hantering av Internet of Things (IoT)-miljöer, men vi kan inte förlita oss på den tekniken. Bärbara enheter blir allt mognare och finns i många olika formfaktorer, inklusive huvudburna skärmar (eng. *head-worn displays [HWDs]*), smarta klockor och smarta armband. Den här typen av enheter gör det möjligt att lätt få tillgång till information. De är avsedda att alltid vara aktiva och känner av den omgivande miljön för att kunna erbjuda ett bättre användargränssnitt. Förstärkt verklighet (eng. *augmented reality [AR]*) är en teknik som lämpar sig för dessa typer av användargränssnitt tack vare dess förmåga att sammanföra det virtuella med det verkliga. Att bygga prototyper för att upptäcka och styra saker med AR som användargränssnitt kan emellertid vara både svårt och dyrt, eftersom detta innefattar ett antal olika enheter och system med varierande teknisk mognad.

Syftet med den forskning som presenteras i denna avhandling var att utveckla och utforska tre verktyg som kan användas för att bygga och experimentera med prototyper av AR och IoT interaktion och att introducera fyra interaktionsmodeller för att kunna kontrollera IoT enheter. Ett av verktygen är baserat på Wizard of Oz (WOZ)-metoden som låter en människa simulera outvecklade delar av ett tekniskt system och de två andra bygger på virtual reality-teknik. Interaktionsmodellerna är utvecklade för olika formfaktorer. Den första är baserad på en smart klocka och kallas för *UbiCompass*. De övriga tre interaktionsmodellerna baserar sig på HWD-formfaktorn, och benämns *Floating Icons*, *World in Miniature* och *Floating Menu*.

Avhandlingen omfattar fem artiklar.

Artikel 1 introducerar ett WOZ-verktyg kallat WozARd. WozARd möjliggör för en testledare att styra den visuella, taktila och auditiva stimuli som presenteras för testdeltagare. Studien som beskrivs i artikel 1 är en första undersökning av WozARd-metodens förmåga att simulera en trovärdig illusion av en verklig AR-stadstur. En användarstudie genomfördes genom att samla in och analysera kvalitativ och kvantitativ data från 21 deltagare som utförde AR-stadsturen med hjälp av WozARd kopplad till en HWD och en Sony SmartWatch. Dataanalysen fokuserade på sju kategorier som bedömdes kunna ha en inverkan på hur WozARd-metoden uppfattades av deltagarna: precision, relevans, responsivitet, teknisk stabilitet, visuell trovärdighet, allmän användarupplevelse samt testledarens prestationsförmåga. Sammantaget visade resultaten från användarstudien på att deltagarna upplevde den simulerade AR-stadsturen som en relativ realistisk upplevelse trots viss teknisk instabilitet och misstag av testledaren.

Artikel 2 presenterar en VR-baserad verktyg kallad IVAR (Immersive Virtual AR). Tanken med den VR-baserade metoden är att kunna bygga och utvärdera prototyper av bärbar AR- och IoT-interaktion i en virtuell miljö. IVAR utvecklades i en iterativ designprocess som resulterade i en testbar uppställning med avseende på hård-och mjukvara. Dessutom genomfördes ett pilot-experiment med 24 deltagare för att undersöka vad det innebär att samla kvalitativ och kvantitativ data med den föreslagna metoden. Det viktigaste bidraget från studien är att IVAR visar potential att bli ett användbart verktyg för att bygga och utvärdera prototyper av bärbar AR- och IoT-interaktion. Dock kvarstår flera utmaningar innan meningsfull data kan samlas in i kontrollerade experiment. Framför allt spårningstekniken (eng. *tracking*) måste förbättras med avseende på precision och påträngdhet.

Artikel 3 presenterar en VR-baserad metod för att använda VR-teknik med “room-scale tracking” som ett prototypverktyg för att utforska IoT-interaktion. Vi kallar prototypverktyget för VRUbi. Tre olika IoT-interaktionskoncept jämfördes i ett kontrollerat experiment med 21 testpersoner för utvärdering och jämförelse. Vissa statistiskt signifikanta skillnader och subjektiva preferenser kunde observeras i respektive kvantitativa och kvalitativa data. Det viktigaste kunskapsbidraget handlar om nyttan av att använda VR som ett prototypverktyg för att utforska IoT-interaktion.

Artikel 4 presenterar ett nytt IoT-interaktionskoncept kallat UbiCompass. En prototyp av UbiCompass-konceptet utvecklades för en smart klocka och integrerades med ett befintligt smarthem system. Denna jämfördes sedan med en traditionell mobilapplikation för styrning av smarta hem, i ett kontrollerat experiment med 36 deltagare. Resultaten visade statistiskt signifikanta skillnader till förmån för det föreslagna konceptet. Detta belyser den potential som UbiCompass har som IoT-interaktionskoncept.

Artikel 5 presenterar tre grundläggande AR-interaktionsmodeller, med fokus på upptäckt och val av IoT-enheter, implementerade för Microsoft HoloLens. Syftet var att jämföra de tre interaktionsmodellerna i en experimentell studie med 20 deltagare. Deltagarna delades in i två grupper; en med få virtuella enheter och en med många virtuella enheter. Varje grupp skulle lösa samma uppgift med var och en av de tre interaktionsmodellerna. Resultaten visade att med få IoT-enheter att hantera skiljer sig deltagarnas interaktioner inte signifikant. Däremot med många enheter att interagera med framstod interaktionsmodellen World in Miniature som särskilt svår och tidskrävande. Det fanns också stor variation i vilken modell som föredrogs av deltagarna, vilket möjligen innebär att en kombination av de tre föreslagna modellerna är önskvärt i ett fullt utvecklat AR-system för hantering av IoT-enheter.

Sammantaget förefaller de tre verktygen WozARd, IVAR och VRUbi vara användbara för att bygga och utvärdera prototyper av bärbar AR-och IoT-interaktion. En viktig kunskap att ta med sig från avhandlingen är värdet av att använda VR för att simulera olika scenarier och interaktioner. Detta kan vara speciellt intressant för organisationer som utvecklar IoT-system eller –tjänster. De VR-baserade prototypverktygen är lämpliga för simuleringar av mer komplexa scenarier bland annat eftersom registrering och tracking enkelt kan simuleras. WozARd däremot lämpar sig för prototyper av enklare användargränssnitt för AR.

Sammantaget bygger de presenterade interaktionsmodellerna på två formfaktorer, smart klocka och HWD, som båda gjorde bra ifrån sig under experimenten. De är båda fokuserade på tre aspekter: att upptäcka IoT-enheter; att välja och kontrollera IoT-enheter; och att användaren inte behöver starta en applikation, användargränssnittet ska helt enkelt dyka upp när en person kommer in t ex i ett smart kontor.

# List of included papers

## Paper 1: WozARd: A Wizard of Oz Method for Wearable Augmented Reality Interaction – A Pilot Study

Alce, G., Wallergård, M., and Hermodsson, K. (2015). WozARd: A Wizard of Oz Method for Wearable Augmented Reality Interaction – A Pilot Study. *Advances in Human-Computer Interaction*, 2015, 3. DOI: 10.1155/2015/271231

This paper briefly describes a Wizard of Oz tool called WozARd. Additionally, a pilot study was conducted to perform an initial investigation of the capability of the WozARd method to simulate a believable illusion of a real working AR city tour. Master thesis students developed the first version of the tool. The respondent developed new features, stabilized the original version and redesigned the user interface. Moreover, the respondent was responsible for designing, planning, and executing the experiment; for the analysis of the data; and for writing the paper. Mattias Wallergård helped to plan the experiment. He also critically reviewed the text along with Klas Hermodsson.

## Paper 2: A Prototyping Method to Simulate Wearable Augmented Reality Interaction in a Virtual Environment – A Pilot Study

Alce, G., Hermodsson, K., Wallergård, M., Thern, L., and Hadzovic, T. (2015). A Prototyping Method to Simulate Wearable Augmented Reality Interaction in a Virtual Environment – A Pilot Study. *International Journal of Virtual Worlds and Human Computer Interaction*, 3, (pp.18-28). DOI:10.11159/vwhci.2015.003

This paper describes a VR-based prototyping tool that was used for simulating wearable AR and IoT interaction in a virtual environment with relatively inexpensive, off-the-shelf devices. The work was developed and presented in a master thesis by Lars Thern and Tarik Hadzovic. The respondent was responsible for designing, planning, and executing the experiment; for the analysis of the data; and for writing the paper. All five authors jointly analyzed the data, wrote the paper and critically reviewed it.

## Paper 3: Using VR as Prototyping Tool for IoT Interaction in a Smart Home Environment

Alce, G., Ternblad, E., and Wallergård, M. (2017). Using VR as Prototyping Tool for IoT Interaction in a Smart Home Environment. Submitted to *Virtual Reality Springer Journal*.

This describes how the VR technology based on room-scale tracking can be used to prototype IoT interaction. Three IoT interaction concepts were compared in a controlled experiment for evaluation and comparison. The respondent was responsible for designing, planning, and executing the experiment; for the analysis of the data; and for writing the paper. Eva-Maria Ternblad, Mattias Wallergård and the respondent jointly wrote the paper and critically reviewed it.

## Paper 4: UbiCompass: An IoT Interaction Concept

Alce, G., Espinoza, A., Hartzell, T., Olsson, S., Samuelsson, D. and Wallergård, M., (2018). UbiCompass: An IoT Interaction Concept. Advances in Human-Computer Interaction, 2018. DOI: https://doi.org/10.1155/2018/5781363

This paper introduces an IoT interaction concept called UbiCompass. It runs as a watch face and can control other IoT off-the-shelf devices. Additionally, this paper presents a user study that compares UbiCompass with a traditional application running on a smartphone. The work was carried out and presented in a master thesis by Dennis Samuelsson. The respondent was responsible for designing, planning, and executing the experiment; for the analysis of the data; and for writing the paper. All six authors jointly wrote the paper and critically reviewed it.

# Paper 5: AR as a User Interface for The Internet of Things – Comparing Three Interaction Models

Alce, G., Roszko, M., Edlund, H., Olsson, S., Svedberg, J. and Wallergård, M. (2017). AR as a User Interface for The Internet of Things – Comparing Three Interaction Models. *Proceedings of the 16th IEEE International Symposium on Mixed and Augmented Reality* (ISMAR), (pp. 81-86). DOI: 10.1109/ISMAR-Adjunct.2017.37.

This conference paper presents three AR interaction models used to control IoT devices. The AR user interface was implemented for the Microsoft HoloLens. Additionally, a comparative study was conducted between two groups, one with low device density and one with high device density. The respondent was responsible for designing, planning, and executing the experiment; for the analysis of the data; and for writing the paper. All six authors jointly wrote the paper and critically reviewed it.

# Other publications by the respondent

Alce, G., Hermodsson, K. and Wallergård, M. (2013). WozARd: A Wizard of Oz Tool for Mobile AR. *Proceedings of the 15th International Conference on Human-Computer Interaction with Mobile Devices and Services* – MobileHCI '13. (pp. 600-605). ISBN: 9781450322737.

Alce, G., Thern, L., Hermodsson, K. and Wallergård, M. (2014). Feasibility Study of Ubiquitous Interaction Concepts. *Proceedings of the 6th International Conference on Intelligent Human-Computer Interaction* – iHCI '14. (pp. 35-42). DOI: 10.1016/j.procs.2014.11.007.

Chippendale, P., Prestele, P., Buhrig, D., Eisert, P., BenHimane, S., Tomaselli, V., Jonsson, H., Alce, G., Lasorsa, Y., de Ponti, M. and Pothier, O. (2012). VENTURI – immersiVe ENhancemenT of User-woRld Interactions. White Paper. https://venturi.fbk.eu/documents/2012/09/venturi-white-paper-year-1.pdf.

*Chippendale, P., Tomaselli, V., D'Alto, V., Urlini, G., Modena, C.M., Messelodi, S., Strano, M., Alce, G., Hermodsson, K., Razafimahazo, M., Michel, T. and Farinella, G.M.* (2015). Personal Shopping Assistance and Navigator System for Visually Impaired People. In: Agapito L., Bronstein M., Rother C. (eds.) Computer Vision - ECCV 2014 Workshops. ECCV 2014. Lecture Notes in Computer Science, vol. 8927. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-16199-0_27. Online ISBN: 978-3-319-16199-0.

# Introduction

Imagine the following scenario:

*Gary enters conference room number 1805, which belongs to a venture start-up in Palo Alto, California. The time is 09:45 AM (PST) and the room is empty. He is 15 minutes early for his presentation. This is his first visit and so he needs some time to set up everything. The room is equipped with the latest high-tech sensors and smart devices. Gary, who is not so tech savvy, is open to trying out new technology. He recently bought a pair of smart glasses developed by a company called Elma. He also loves to carry his new fashionable smartwatch that you do not need to think about charging and finally, his new handy smart belt. According to his friend Matthew, the belt helps the glasses and the watch by providing them with power, but also by amplifying the signals used for communication. He is a bit nervous since he is not very good with new technology; he usually needs a lot of help. According to Matthew, this system is so intuitive that even Gary will be able to use it. When Gary glances at the table he can see a hologram representing the room in a miniature. He can see which devices he has access to and can control: the projector, the sound system and the window blinds. Looking around the room, he can see holograms that help him to set up his presentation. Gary manages to do so with a simple click on his watch. Next, the system carries out a sound check for him, which Gary finds convenient. Next, he notices how virtual objects above the window blinds shake to attract his attention. The system suggests that it might be a good idea to pull them down since the bright sun is shining in on the right side of the room. An animation shows Gary that he can take control of the blinds with a click of his watch. Then he makes a mid-air gesture with his watch that lowers the blinds. Now, Gary feels confident and ready to make his presentation with the new technology. He can relax.*

*The other participants start to arrive. The camera in the room detects all the people who enter. When they are all in place, the system indicates this to Gary on his glasses. Now, he can start.*

*The presentation proceeds. The audience finds Gary's presentation very interesting.*

*When the presentation is over, Gary takes off his glasses and is immediately back in his working room at home in Sweden. The time in Sweden is 20:00 (CET), right on time for the goodnight story that Gary always reads to his two boys from a good old-fashioned book.*

Similar to the science fiction TV series called "Black Mirror", the scenario is a familiar situation but with a boost of new technology. All of the technologies in the scenario are emerging and some parts of the scenario can already be experienced with the current technologies. The emerging technologies that are needed to experience a similar scenario are the Internet of Things (IoT), augmented reality (AR) technology, wearables, and virtual reality (VR) technology.

To date, IoT researchers have focused on two main enabling factors: the integration of several technologies and communication solutions (Atzori, Iera, & Morabito, 2010). This is probably one of the reasons IoT devices for smart workspaces are still in the innovation trigger phase in the Gartner Hype Cycle for Emerging Technologies (Figure 1). However, IoT devices are on their way up in the cycle and getting close to the peak of inflated expectations. To reach mainstream consumers it is important to start exploring applications and interaction models for end users. For example, less effort has been devoted to exploring how a not-so-tech-savvy end user can discover and directly interact with the numerous connected things predicted by the IoT vision.

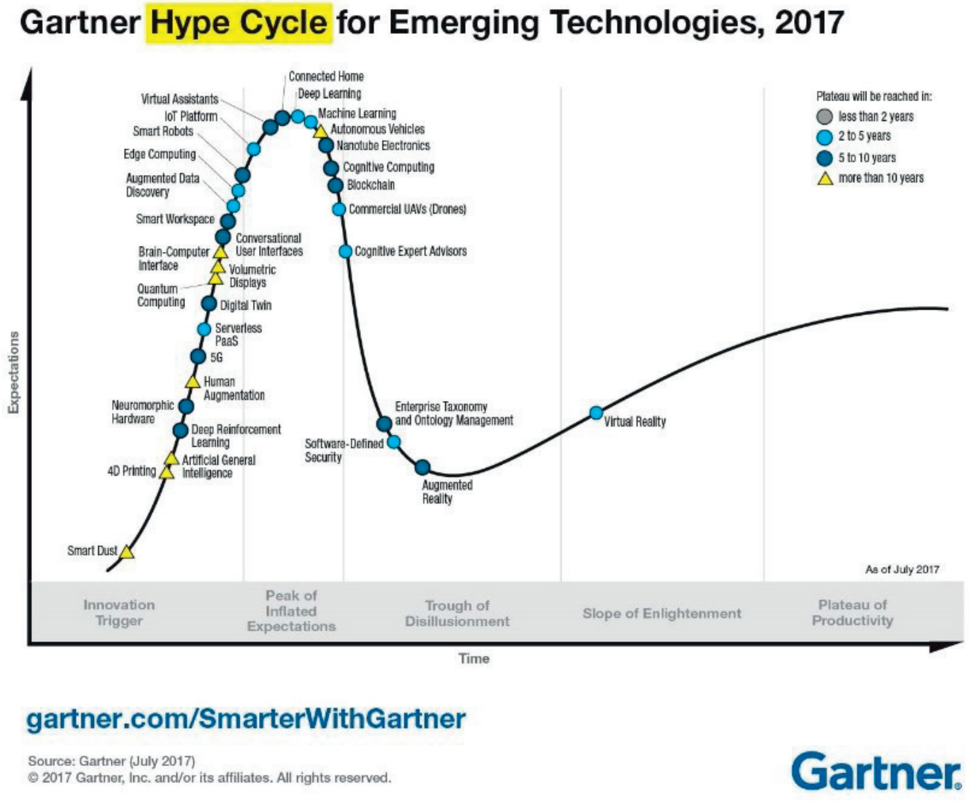

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**Figure 1.** Gartner Hype Cycle for Emerging Technologies, 2017. Image courtesy of Garnter Inc.

There are good reasons to assume that the combination of using AR as a user interface and wearables to control and present the user interface can open up opportunities to experience the scenario. Additionally, the combination of AR and wearables will likely help people in their daily routines to control things in a more natural manner and to discover new things that improve their quality of life.

At the core, AR transforms volumes of data and analytics into images or animations that are overlaid on the real world. AR technology is one of the top trends in the Gartner Hype Cycle for emerging technologies 2017 (Panetta, 2017) but has not passed the trough of disillusionment yet and is still in its infancy (Figure 1). Nevertheless, big companies such as Facebook, Apple, and Google have invested a lot in AR technology and have introduced AR platforms, such as ARKit by Apple, and ARCore by Google for their respective smartphone platforms. Today most AR applications are delivered through smartphone devices. Smartphones have become relatively inexpensive and have powerful embedded processors and sensors that are needed to experiencing AR. Many people are familiar with simple AR entertainment applications, such as the game Pokémon GO and Snapchat Filters. The idea of using the smartphone as the enabler of AR technology is to let a much broader audience experience AR through their own smartphones. Through the smartphone, AR will reach the mainstream consumers but the foundational idea of AR is to immerse the user in a mixed physical/virtual world, where relevant virtual information is presented around them. However, holding the smartphone up to look "through" an AR application is awkward both physically and socially (Barba, MacIntyre, & Mynatt, 2012). This kind of experience also suffers from the so-called "keyhole" problem, where users are forced to interact with their surroundings through a screen, using a camera to recreate reality (Hermodsson, 2010). This creates a disconnect between the user and the surrounding environment limiting the usability. To enable serendipity as in the scenario, and more comfortable interactions, we need to look at the next generation of consumer electronics for help. Today, we can already see a shift from smartphones to hands-free wearables such as head-worn displays (HWDs) which are also referred to as smart glasses or head-mounted displays. In this thesis, the term HWD is used.

The HWD is one example of wearables, but there are many other form factors available including smartwatches and wristbands (Genaro Motti & Caine, 2014). Wearable devices enable information at a glance (Baker, Hong, & Billinghurst, 2014). They are intended to always be "on", to always be acting and to always be sensing the surrounding environment in order to offer a better interface to the real world (Rekimoto, Ayatsuka, & Hayashi, 1998). Ideally, in a world where the digital and physical are bridged, users would not think of how to interact with systems. Everything would just seamlessly work perfectly as in the scenario. In the last couple of years, several HWDs have appeared on the market, such as Microsoft HoloLens (Microsoft, 2016), ODG R7 (Osterhout, 2016) and Meta 2 (Meta, 2017). Although, the HWDs are still in developer versions, they have a promising future for offering a good AR experience and for presenting a user interface that can be used to control connected smart IoT devices.

According to the Gartner Hype Cycle (Panetta, 2017), VR technology has passed the trough of disillusionment (Figure 1) and is heading up the slope of enlightenment. The newer VR products based on room-scale tracking are much more stable and mature. The next step that everybody is waiting is for VR to reach mainstream consumers.

This thesis presents results of research on how to prototype IoT interaction. It also presents interaction models that can be used to discover, select and control IoT devices. The role of AR has been as a user interface for IoT interaction, while the role of VR has been to simulate different testable IoT environments.

We have identified two key challenges with a bearing on our research vision:

- Prototyping methods for IoT interaction
- Exploring interaction models for IoT environments

**Prototyping methods for IoT interaction.** As Davies et al. (2005) noted, it is difficult and time consuming to prototype and to evaluate this new design space due to components that are undeveloped or not sufficiently advanced. To overcome this dilemma and focus on the design and evaluation of new user interfaces instead, it is essential to be able to simulate quickly undeveloped components of the system to enable the collection of valuable feedback from potential users. In this thesis, two methods are presented for prototyping IoT interaction: real-world prototyping with WOZ, and VR-based prototyping.

**Exploring interaction models for IoT environments.** IoT interaction can be roughly divided into two types: explicit and implicit (Poslad, 2009). Pure, explicit interaction is context free, which means that users must repeat the required action every time (e.g., pressing a switch to turn a light on or off). Built on implicit interaction, the same example can be achieved with a sensor that monitors when people enter a room and automatically switches on the light for those who are authorized. This thesis presents interaction models for IoT environments using both the smartwatch and the HWD form factors. The interaction models explore a combination of explicit and implicit interaction.

By using the prototyping methods, interaction models and form factors that are presented, the scenario described at the beginning of this introduction can be experienced, at least on an elementary level.

## Research objectives

There are two overall objectives of this thesis:

1. To explore how to prototype IoT interaction for not-so-tech-savvy users by using wearables both as input devices to control things and as output devices to present both visual and auditory user interfaces.
2. To explore how AR can be utilized as a user interface for IoT interaction.

These objectives were achieved by addressing the following questions:

1. How do you prototype quick and easy AR user interfaces with a mid-fidelity experience? (Paper 1)
2. How can VR be used as a prototyping method for IoT interaction? (Papers 2 and 3)
3. How can the watch form factor be used for not-so-tech-savvy users, to discover and control IoT devices? (Paper 4)
4. How does scaling up the number of connected devices effect AR interaction models? (Paper 5)

## Navigating the emerging technology landscape

In the course of carrying out the research presented in this thesis, we have seen the rise of the emerging technologies of IoT, AR, wearables and VR. Since the agreement between Sony and Lund University that got me involved in the EASE Project (Industrial Excellence Centre for Embedded Applications Software Engineering) (EASE, 2008) back in 2011 (Figure 2), we have constantly worked iteratively with workshops and brainstorming sessions to come up with new ideas but also to decide which technology to work with. Moreover, we were flexible and tried to take on whatever new and emerging technologies appeared during this time and then went on to build prototypes with them.

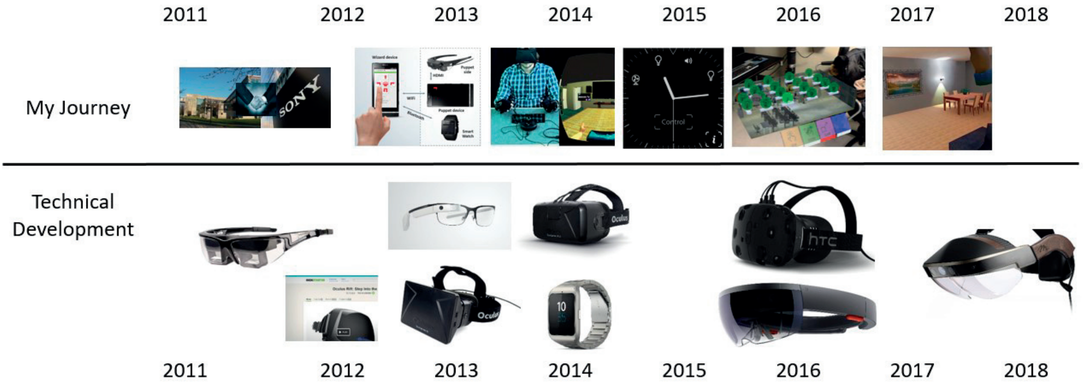


**Figure 2.** Timeline of the emerging technologies available at the time.

The Vuzix Star 1200, which became available late 2011 early 2012, could only be used as a non-interactive display. Thus, we connected it to a smartphone and built a tool to prototype AR and IoT interaction. When the Oculus DK1 arrived back in 2013, we started to investigate the possibility of using VR to prototype AR and IoT interaction, although the Oculus DK1 had limited tracking and poor resolution. When we saw that wearables started to become available and were relatively mature, such as the Sony Smartwatch 3 back in 2014, we built a user interface for the watch form factor to study how far we could get using only that form factor. When the Microsoft HoloLens became available, we built three AR interaction models for the HWD form factor to study the differences between the interaction models, but also to study what happens if we scale up the number of IoT devices.

# Theoretical overview

This chapter provides the reader with a basic description of the areas the thesis covers. It starts by introducing the Internet of Things (IoT) and moves on to describe augmented reality (AR) technology and its application areas. The section that follows is concerned with wearable technology and its benefits and limitations. Virtual reality (VR) is then introduced along with its technology and application areas. The chapter concludes with the design process and prototyping methods.

## Internet of Things

To date, there is no academic definition of the Internet of Things (IoT). Nevertheless, Rogers et al. (2011) define IoT as "a system of connected computing devices, mechanical and digital machines, objects, animals or people that are provided with a unique identifier and the ability to transfer data over a network."

In an IoT network, data can be exchanged without requiring human-to-human or human-to-computer interaction. A "thing" in the IoT can be a person with a heart monitor implant; a farm animal with a biochip transponder; an automobile that has built-in sensors to alert the driver when tire pressure is low; or any other natural or man-made object that can be assigned an IP address and provided with the ability to transfer data over a network (Figure 3). Another academic terminology used more often is "ubiquitous computing" (UbiComp). The idea of technology becoming ubiquitous in everyday life is not new, though. This development was already foreseen almost 20 years ago by Weiser (1999). As the VR vision of computing was fading into the background, the new vision of UbiComp offered by Weiser was replacing it (Barba et al., 2012). In many ways, this view was the antithesis of the VR view. Instead of inserting ourselves into the virtual world of the computer, UbiComp had us inserting computers into everything around us. UbiComp saw the world as a rich environment of hidden information and capabilities, waiting to be made available to us and responding to our needs, both hidden and obvious.

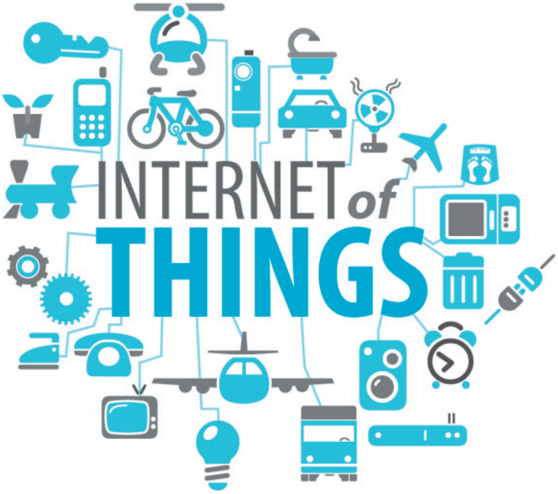


**Figure 3.** A network with devices connected to the Internet. Image courtesy from Sriramkumar (2016).

## Augmented Reality

In this thesis research, augmented reality (AR) technology has been used as a user interface to control IoT connected devices, similar to what happens in the scenario. AR is a technology that uses display, tracking, and other sensors to enhance (augment) the user's senses in the real-world environment with computer generated objects or information. A common academic definition is Azuma's (1997): AR as a system that has three characteristics:

1. Combines real and virtual
2. Interactive in real time
3. Registered in 3D

This definition allows other senses than vision to be augmented. This means that AR can also be used to augment or substitute users' missing senses by sensory substitution, such as augmenting the sight of blind users or users with visual impairment by the use of audio cues, or augmenting hearing for deaf users by the use of visual cues (Carmigniani & Furht, 2011). Examples of sensors that can be used to augment our senses are a Geiger counter that can sense and measure radiation, infrared sensors that do the same for infrared light, and ultrasonic microphones that detect frequencies outside the audible range of human hearing (Mateevitsi, Haggadone, Leigh, Kunzer, &

Kenyon, 2013). Other senses that can be augmented are smell, touch, temperature, and taste. This type of information could be communicated to the user and be used to augment his or her senses in different situations. However, when it comes to the first point in Azuma's definition regarding combining real and virtual, the traditional focus in the research field has been on the visual modality, that is, the display technology.

## AR technology

There are several types of AR technology and a basic distinction can be made by proceeding from Azuma's definition. As already mentioned, in order to combine real and virtual things, different display technologies can be used. The two most common technologies are smartphone displays and head-worn displays (HWDs), which are sometimes referred to as glasses.

Different input techniques are used in order to interact with the virtual objects. The input methods have changed from physical controls like buttons, switches, keyboards, and mice, to touchscreens, sensors, voice, eye tracking, and gestural means of triggering interactions.

In order to register virtual things correctly in the real world, advanced tracking is needed. The AR community has focused on tracking since the beginning of AR and is still doing so. The most commonly used tracking techniques use computer vision (CV), GPS and inertial sensors. CV renders 3D virtual objects from the same viewpoint from which the images of the real scene are being taken by tracking cameras (Carmigniani & Furht, 2011). AR image registration uses different methods of CV, mostly related to video tracking. These methods usually consist of two stages: tracking, and reconstructing/recognizing. Fiducial markers (Figure 4a) are the most common markers used for recognition. Interest points are detected in the camera images and used to recognize unique patterns. Smartphones, due to their development, are now able to locate and map the world by combining different sensors from the phone, such as CV and inertial sensors. This tracking technique is called SLAM (Simultaneous Localization and Mapping) (Figure 4b). SLAM technology is used in ARKit (Apple, 2017), which is a new framework that allows you to create AR experiences for the iPhone and iPad. SLAM is also used in ARCore (Google Inc., 2017), which is Android's counterpart to ARKit.

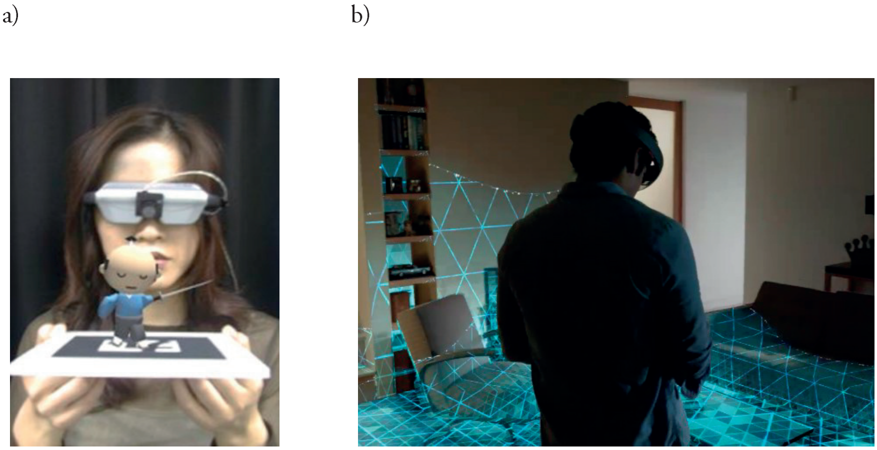


**Figure 4.** a) Fiducial marker tracking. Image courtesy of ARToolKit (2004), b) SLAM tracking. Image adapted from Smeenk (2016).

## Application areas for AR

There are many possibilities for using AR in an innovative way. Examples of areas that recently have gained the most attention are entertainment, social applications, on-site repair or maintenance, museum tours, and medical.

One entertainment application that has become very famous is the Pokémon GO application (Figure 5a). In the game, the user needs to catch Pokémon's in different places. They can appear in your office, for instance (Figure 5a). An example of a social application that has also become famous is Snapchat (Figure 5b). Snapchat augments different characters onto your face and lets you take a picture and share the photo with others. Both applications enable the AR experience through the smartphone form factor.

To date, one of the best AR glasses that enables AR experiences is the Microsoft HoloLens (Figure 6). You as a user can put holograms around your living room, or on a screen on the wall showing YouTube or Netflix. It also allows you to put virtual notes on the refrigerator and see how the weather is in a specific place (Figure 6).

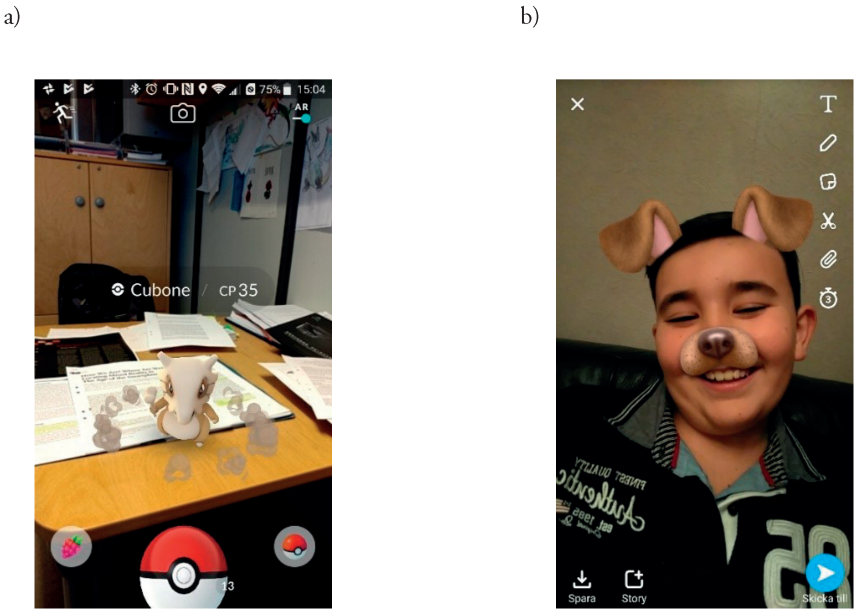


**Figure 5.** a) Pokémon GO in the office, b) Snapchat adding a character onto your face. Image courtesy of Berk Alce.

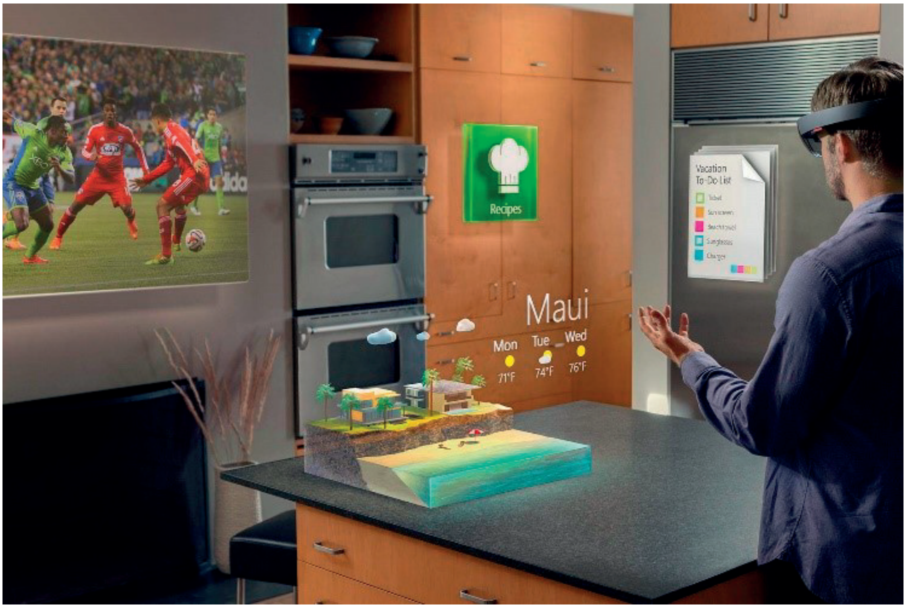


**Figure 6.** Example of an AR application superimposing virtual objects on the real world through the Microsoft HoloLens. Image adapted from Coldewey (2015).

# Wearable technology

This section gives an overview of wearable technology form factors and their benefits and limitations. The head-worn display (HWD) and smartwatch form factors are the two wearables that were used in the thesis research and are thus in focus.

## Overview

We have reached a point where hundreds of companies, both old and new, now believe that wearable devices and the infrastructure to support them are practical and achievable (Baker, Hong, & Billinghurst, 2014). Wearable technology is based on computational power integrated into users' clothing or attached to their bodies in some way. According to Mann (2014), wearable computing is defined as "the study or practice of inventing, designing, building, or using miniature body-worn computational and sensory devices." This means the device will be worn and will always be on and running (Mann, 1998a). Different form factors have been experimented with to provide the user with a means of interacting with digital information while on the move in the physical world. Examples of such form factors are the smart ring (Smith, 2017), Boy-Coupled FingerRing (Fukumoto & Tonomura, 1997), clothing such as Levi's smart jacket (Levi's, 2017), jewelry such as the Misfit's smart necklace (Misfit Shine Bloom Necklace, 2015), and earphone such as Jabra Sport Pulse (2015), which can track your heart rate (Figure 7).

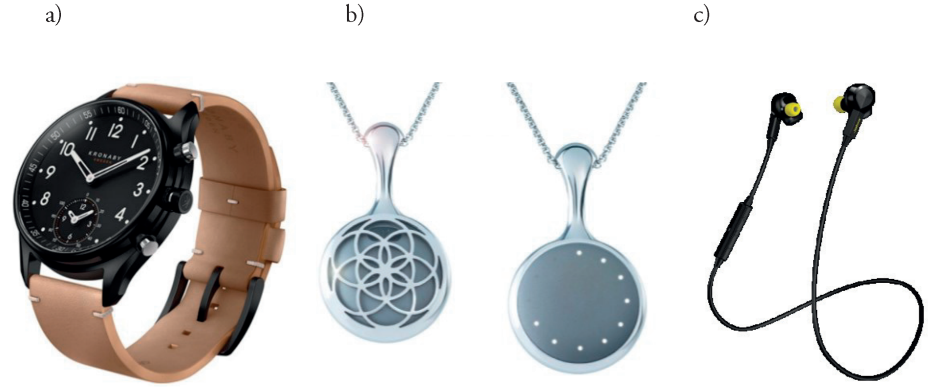


**Figure 7.** Examples of wearable devices: a) Kronaby Watch (2015), b) Misfit Shine Bloom Necklace (2015), c) Jabra Sport Pulse (2015) which tracks heart rate.

According to Billinghurst & Starner (1999), the elements of a wearable device work to satisfy three goals. The first and most obvious is that it must be mobile. By definition, a wearable must go where its wearer goes.

The second goal is to augment reality, for example, by overlaying computer-generated images or audio in the real world.

The third goal is to provide context sensitivity. When a computer device is worn, it can be made aware of the user's surroundings and state. Context-sensitive applications can be developed to exploit the intimacy between the human, the computer, and the environment.

## Head-worn display

The most common AR display technologies are see-through HWDs that can be either optical or video. *Optical see-through* displays (Figure 8) place optical waveguide combiners in front of the user's eyes; the combiners are partially transparent so that the user can see the real world through them and partially reflective so that the user can see virtual images reflected from small head-worn screens. Several manufactures including Microsoft HoloLens (Microsoft, 2016), Epson Moverio (2015) and Sony SmartEyeglass (2015) are built on this display technology, which is referred as holographic waveguides (Yang, Twardowski, Gérard, & Fontaine, 2016). *Video see-through* displays work by streaming real-time video from head-worn cameras to the graphics subsystem. This renders virtual computer graphics images into the video buffers in real time, blending the virtual and real (Bowman, Kruijff, LaViola Jr, & Poupyrev, 2004).

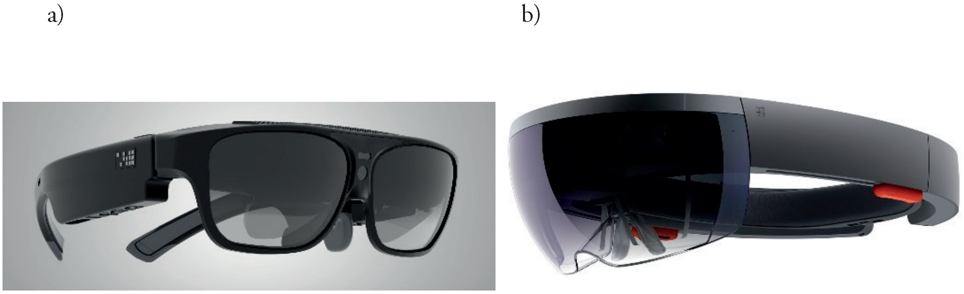


**Figure 8.** Examples of optical see-through HWDs: a) ODG R-7 (Osterhout, 2016), b) Microsoft HoloLens (Microsoft, 2016).

On the research front, there are lasers that can directly "draw" on the retina (Figure 9a). It is called the Virtual Retina Display (VRD) and was invented in the Human Interface Technology Lab in 1991 (Furness & Kollin, 1992). With a VRD, photon sources are used to generate coherent light rays (such as lasers) that allow the system to draw a picture on the retina. To produce full-color images, you need to use three light sources (red, green and blue), while monochrome versions of VRD require only one. These light rays are intensity modulated to match the intensity of the image reproduced, which means that it is possible to produce fully enclosed and see-through displays. The VRD has great potential and can provide a high-quality field of view that almost approaches that of the human eye with high-resolution stereo images. Magic Leap (Figure 9b), which has received huge investments from Google, among others, is rumored to be based on the same technology as VRD.

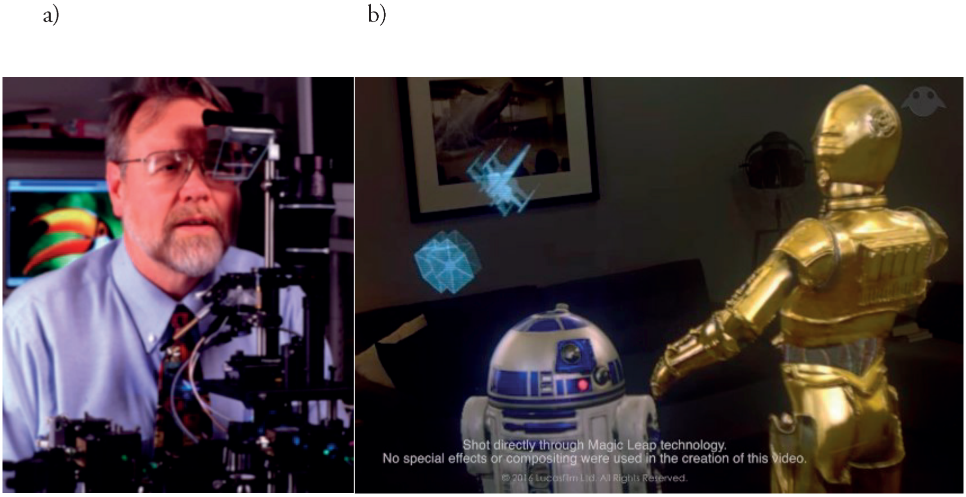


**Figure 9.** a) Virtual Retinal Display Optical Bench (Digi-arts, 2017). Image courtesy of Tom Furness, b) Magic Leap Star Wars demo through see-through glasses. Image courtesy of Magic Leap (2017).

### *Benefits*

One of the biggest advantages of HWDs is that the user can have complete physical visual immersion because the user always sees the virtual and real worlds regardless of head position and orientation (LaViola Jr, Kruijff, McMahan, Bowman, & Poupyrev, 2017). HWDs can also offer instant information before one's very own eyes that is contextually relevant to an ongoing activity and that can be viewed surreptitiously, without having to physically pull out a smartphone (Rogers et al., 2011). However, it is easy to cross the boundary between useful information and overwhelming clutter. In order to assist the user unobtrusively, the HWD must model its user's knowledge, actions goals, and even emotions. To date, computer user interfaces have mostly ignored human affect. However, HWDs and wearables in general, which are in contact with their users in many different contexts, allow an unprecedented opportunity for affect sensing, for example, if the user is tired, happy or sad (Starner et al., 1997). Another benefit is that an HWD offers hands-free interaction, which is very practical in several situations. One example is when you are pushing a trolley and talking with someone on a smartphone, another is when you are doing maintenance work and talking or reading instructions, and a third is in a hospital environment where it is particularly important during operations or in clean rooms.

### *Limitations*

HWDs have several limitations including esthetics (e.g., all the available devices are too bulky) and ergonomics (e.g., not comfortable to wear and too heavy). Battery life is also a great problem; in the initial version, Google Glass could last a day with moderate usage, but with new updates and with new features the battery last hardly half a day. HoloLens lasts only about two hours; on the other hand, it is uncomfortable to wear for a longer time. Several problems still remain both for AR and VR HWDs including technology issues such as processing tracking, optics resolution, field of view, social issues such as privacy, design, and awkward interaction (Lucero et al., 2013).

## Watch

The wrist has long been a compelling location to place wearable technology (Lyons, 2015). Our usage of watches is also transforming from just showing the time to becoming more and more of a personal computer. In this section, the benefits and limitations will be discussed.

### *Benefits*

Smartwatches (Figure 7) are available on the market and have proven to be more socially viable than HWDs. Most people are comfortable wearing a watch, as opposed to wearing an HWD. Using a wearable to interact with other devices has several benefits, one of them being that the device can almost always be worn and will almost always be on and running (Mann, 1998a). Another motivation for having a watch or a band is to enable people to carry out tasks without having to take out and fiddle a handheld device such as a smartphone.

### *Limitations*

Similar to HWDs, smartwatches also have esthetical challenges. Most of them look too “techy”. Moreover, users are generally unhappy about the frequent recharging requirements, and from a compliance viewpoint, removing the device for recharging presents the risk that the user will not put it back on (Baker et al., 2014). This is generally a strong argument against having yet another device that needs to be recharged, perhaps daily. Recently, however, devices with long-lasting batteries are showing up such as the Kronaby (2017), which has a battery life of two years. Kronaby is a smartwatch that monitors incoming calls and messages but does not have a digital watch face.

## Virtual reality

In this thesis, virtual reality (VR) technology was used to simulate different IoT interactions and environments, similar to the introductory scenario. VR is a technology that uses displays, tracking and other sensors to immerse the user in a virtual environment (VE). A VE uses computer-generated graphical simulations to create “the illusion of participation in a synthetic environment rather than external observation of such an environment” (Gigante, 1993). The term VR is used more specifically to describe the technology that consists of the devices used to generate the virtual environment (Stanney, 2015). However, both terms are used as synonyms.

Two important concepts in the field of VR are “presence” and “immersion.” To date, there is no uniform definition of presence. Witmer and Singer (1998) define it as “the subjective experience of being in one place or environment, even when one is physically situated in another.” According to Slater (1999), presence includes three aspects:

- The sense of “being there” in the environment depicted by the VE.
- The extent to which the VE becomes the dominant one, that is, that the participant will tend to respond to events in the VE rather than in the “real world.”
- The extent to which participants after the VE experience remember it as having visited a “place” rather than just having seen images generated by a computer.

According to Slater (1999), “Immersion is a description of a technology, and describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant.” Factors that contribute to immersion include field of view, resolution, stereoscopy, type of input and latency. In other words, immersion is objective while presence is subjective.

More recently, Slater (2009) argues that there are two orthogonal components that contribute to realistic response in the VE. The first is the place illusion (PI), that is, the feeling of being there. Second, the plausibility illusion (Psi) refers to the illusion that the scenario being depicted is actually occurring. Psi is determined by the extent to which the system can produce events that directly relate to the participant, the overall credibility of the scenario being depicted in comparison with expectation. When both Pi and Psi occur, participants will respond realistically to the VE.

### VR technology

In the last couple of years, a lot of technology that enables VR has gone down in price and is easier to work with. There is a wide range of available systems, such as simple three degrees of freedom (DOF) systems, optical outside-in tracking systems with 6DOF, and inside-out tracking system with 6DOF.

An example of a simple 3DOF system is the Google Cardboard (Figure 10a), which uses the inertial sensors provided by the smartphone to track the user's head. There is no tracking of the user's hand. Google Daydream (Figure 10b) also uses the smartphone sensors to track the user's head but additionally, it uses inertial sensors such as an accelerometer provided by a hand controller in order to track one hand. The controller also has 3DOF tracking, which means the accessory has enough movement and freedom to let it sense when it is going up and down, left and right, and being tilted (Al-Obaidi, 2016). A problem with the inertial sensors is that they tend to drift, which force the user to recalibrate the tracking.

Examples of optical outside-in tracking systems with 6DOF are the Oculus Rift and the HTC Vive (Figure 10c). The Oculus Rift uses optical tracking. Underneath the Rift's fabric cover is an array of infrared micro LEDs that are tracked in real space by the included infrared camera (Oculus, 2017). The Rift features 6DOF position tracking. However, this type of tracking solution forces the user to always face the optical camera in order to have good tracking. The HTC Vive tracking is composed of two agents: the Lighthouse stations and the various sensors on the headset, and VR controllers. Each Lighthouse station is composed of IR LEDs flashing at regular intervals and of two little motors throwing laser beams into the room, one spinning horizontally and the other vertically. The Lighthouse stations irradiate the room sixty times a second with an IR light (Skarredghost, 2017). HTC Vive also features 6DOF position tracking. This technique allows tracking with a sub-millimeter accuracy of both the head and hand controllers. Moreover, it enables room-scale tracking and is not as sensitive to the direction in which the user is looking in order to have good tracking (Lang, 2016). This helps to avoid cyber sickness, which is common when trying out other devices.

Examples of optical inside-out tracking systems with 6DOF are the Samsung Odyssey (Figure 10d) and Lenovo Explorer. Both of them use the same tracking technique called SLAM. This means that they do not need any external sensors to track the movement of the user's head through 3D space. The VR headset builds up a 3D model of the room that the user is standing in by first instructing the user to move his or her head around in order to build up a 3D model that then can be used to understand the user's position in relation to the world. However, this type of tracking solution forces the user to always have the hand controllers within the field of view in order to maintain good tracking.

Achieving accurate tracking is crucial for inducing a sense of higher presence in the user, but it also makes interaction techniques usable in VE applications (Bowman et al., 2004; Cummings & Bailenson, 2016). In many VR applications, it is important for the user interface to provide information about the user's or the physical object's location in the 3D space (Bowman et al., 2004). For example, an application may need the user's head position and orientation so that full motion parallax and stereoscopic depth cues can be included in the application. In another case, the user interface may require information about the position of the user's hand so that a virtual hand corresponding to the user's physical hand can be rendered (Bowman et al., 2004).

**Figure 10.** a) Google Cardboard. Image adapted from (Kambouris, 2014), b) Google Daydream (2016), c) HTC Vive (2016), d) Samsung Odyssey (2017).

## VR applications

There are many applications coming out on the market, and it is hard to find a specific area where VR is not suitable to use. One of the earliest application was by Tom Furness working on one of the first helmet-mounted displays (Figure 11a) for the Air Force from 1966 to 1969. It helped the pilot to see a simplified version of the reality. VR has shown potential in many other areas as well such as cultural heritage (Figure 11b) that utilizes the technology to let the user experience historical sites. Other examples are architecture, city planning and industrial design (Figure 11c). Recently, social VR has gained a lot of interest. Social networks and virtual reality seem like such strange bedfellows, though: one is about connecting you to the world while the other appears to do the opposite. The company behind Second Life has built a new virtual reality platform called Sansar (Ballestrasse, 2017). The VR version is a new social VR application (Figure 11d).

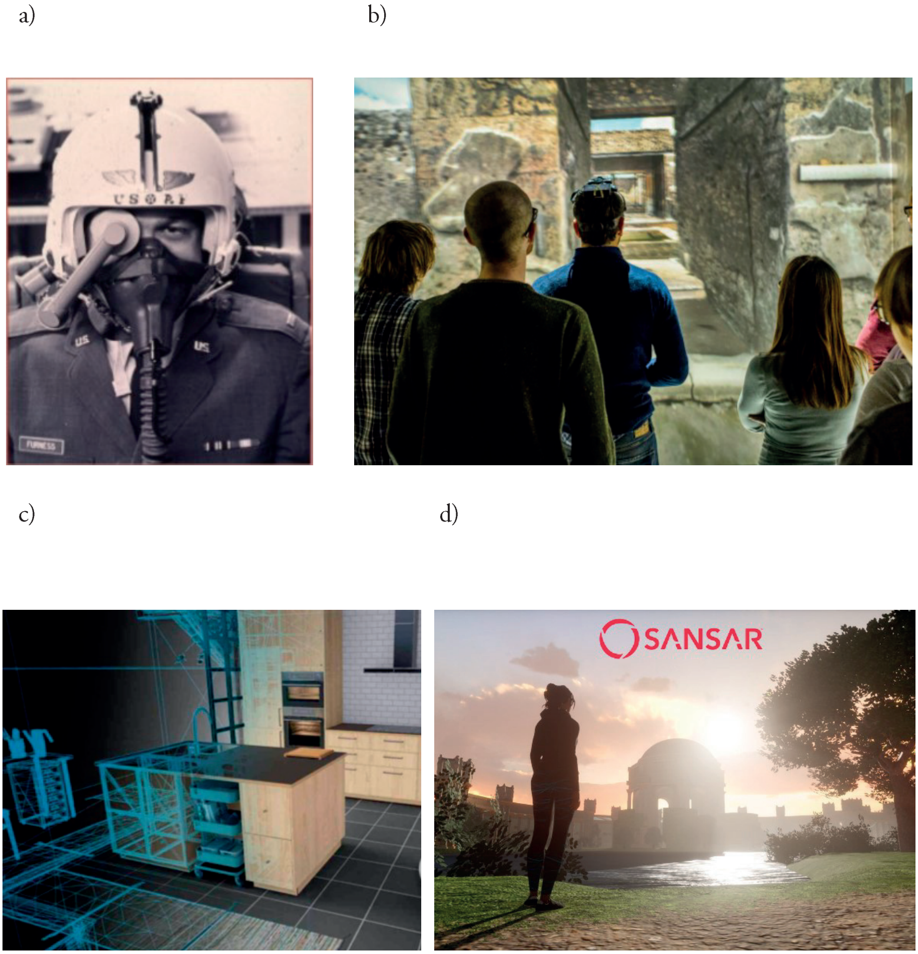


**Figure 11.** a) Tom Furness with one of his first helmet-mounted displays. Image courtesy of Tom Furness, b) Reconstruction of a house in Pompeji (Photo by Kennet Ruona), c) IKEA VR application to explore and design kitchens. Image adapted from Rodriguez (2016), d) The social VR application Sansar from the creator of Second Life. Image adapted from Summers (2017).

## Milgram’s continuum

Milgram’s mixed reality continuum defines the differences between real and virtual environments (Figure 12). The continuum consists of combinations of real and virtual elements (mixed in different proportions), excluding only purely physical and purely virtual realities at either end of the spectrum (Barba et al., 2012). Virtual environments (VE) immerse a user inside a virtual world. As opposed to VE, AR still resides in the real world but provides overlaid virtual information. To summarize, you could say that users of a VE are a part of the computer world while AR aims to make computers become a part of the real world.

**Figure 12.** Mixed reality continuum (Milgram & Kishino, 1994).

The term mixed reality (MR) has lately been used in different communities and forums as a more general term for environments consisting of both physical and virtual objects. One reason is that it is not, like AR, biased towards any of the worlds but quite neutral. However, this has led to confusion since Microsoft is calling all their HWDs for MR despite the fact that some of the models are pure VR HWDs.

## The design process and prototyping methods

Designing an interactive system typically involves an iterative process of brainstorming, prototyping, development, user testing and evaluation (Dow, MacIntyre, Lee, Oezbek, Bolter, & Gandy, 2005). This is not a clear-cut process; the iterations go through many cycles before a final system is achieved. LaViola Jr. et al. (2017) suggest three important tools for exploring design options in the early stages: ideation, sketching and critiquing. Ideation is the process of quickly brainstorming and bodystorming ideas for designs in a creative and exploratory manner. Sketching is the rapid creation of free-hand drawings expressing preliminary design ideas. Both ideation and sketching should be used in a collaborative group process to generate potential designs. Critiquing is then used to review and judge those designs in order to filter and avoid wasting time on poor ideas.

According to Buxton (2010), the early ideation stages is and should be dominated with sketches before moving on to prototypes. Much of this has to do with the related attributes of cost, timeliness, quantity, and disposability.

The prototyping stage brings the design to life; it is the realization of the interaction design. A prototype is an early representation of the design built to model, evaluated and iterated on the design of a product (Hartson & Pyla, 2012). The fidelity of a prototype refers to how completely and closely it represents the intended design (Hartson & Pyla, 2012). Figure 13 is an attempt to show the relation of the fidelity level versus cost of the presented methods.

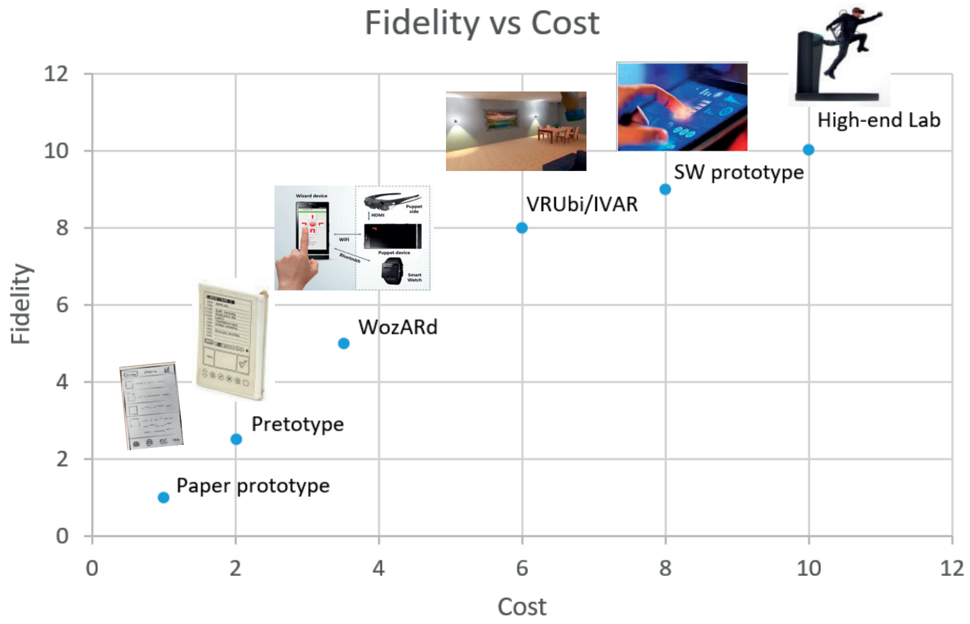


**Figure 13.** The presented tools' fidelity level versus cost.

A low-fidelity prototype provides impressions of the intended design with little or no functionality. Examples of low-fidelity prototypes are scenarios, paper sketches, bodystorming (Figure 14), pretotyping (Figure 15) and Wizard of Oz (WOZ). The idea of bodystorming is that the participants and designers go to a representative environment; if studying a meeting room, they will go to a representative meeting room (Oulasvirta, Kurvinen, & Kankainen, 2003). The idea behind pretotyping (Savoi, 2011) is to start building the design idea with a low-fidelity prototype using cardboard or even a piece of wood, as did Jeff Hawkins, the founder and one of the inventors of the Palm Pilot (Figure 15). The idea behind WOZ is to create the illusion of a working system. The person using it is unaware that some or all of the system's functions are actually being performed by human operator hidden somewhere (Kelley, 1983).

**Figure 14.** Bodystorming an office scenario with paper prototypes and low-fidelity accessory.

**Figure 15.** Jeff Hawkin's wooden PalmPilot (PalmPilot wooden model, 1995).

A mid-fidelity prototype provides the look and feel of the intended design with rudimentary functionality. A mid-fidelity prototype could consist a set of images built with commercial tools such as Invision, Balsamiq and PowerPoint in combination with WOZ.

Finally, a high-fidelity prototype is one that closely resembles the final product. The aesthetics and the interaction of a high-fidelity prototype should be nearly identical to the final product's look and feel.

# Overview of the prototyping methods and interaction models

This section presents an overview of the methods used for prototyping IoT interaction and the interaction models used in this research.

## Prototyping methods

Two main prototyping methods were developed and explored. Real-world prototyping with Wizard of Oz (WOZ) and VR-based prototyping.

### Real-world prototyping with WOZ

The first method is a real-world based prototyping with WOZ. The name of the prototyping tool is WozARd, which was unique at the time of the study since there were no Google Glass or HoloLens available on the market. It was based on Vuzix Star 1200 (Figure 16a), which had to be connected to a display. The Vuzix glasses just mirrored what a display was showing; there was no logic or user interface to interact with and no control. The only way to interact was through the input device, which was connected to the display. A mouse and a keyboard could be used if it was connected to a computer. However, in order to start exploring with futuristic AR interaction and user interfaces, we decided to connect it to a smartphone and let the smartphone be controlled both via a smartwatch for simple interaction and through Wi-Fi by a human wizard. It was a primitive setup but at the time, there was no other WOZ tool that could be used to prototype AR user interfaces that worked with wearables, and both indoors and outdoors (Figure 16b).

WozARd is suitable for AR interaction and user interfaces since it allows an eco-system of wearable devices. It is usable both indoors and outdoors and flexible in terms of being easy to add new user interfaces (Figure 16). See Paper 1 for more details.

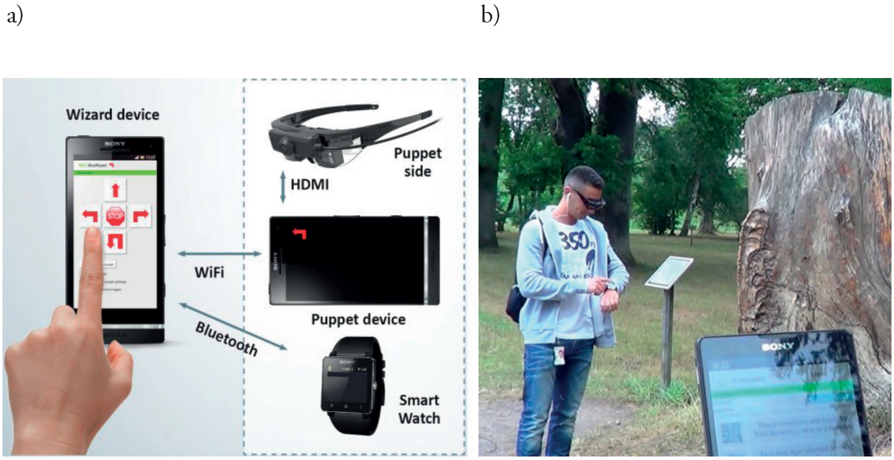


**Figure 16.** a) System overview of WozARd, b) WozARd in use.

Although WozARd is easy and flexible to use, it also has some undeveloped features in need of improvement. These include the registration and tracking of virtual objects and the reliance on a skilled human operator.

## VR-based prototyping

The first VR-based prototyping tool is called IVAR (Immersive Virtual AR) and the second tool is referred to as VRUbi.

**IVAR.** Back in 2013 when the Oculus DK1 arrived, we could see the opportunities the device opened up for prototyping both AR and IoT interaction. This was despite the low resolution of the display, no input was available, and that it only had 3DOF tracking. Together with other off-the-shelf input/output devices, we managed to develop a system that allowed us to prototype wearable AR and IoT interaction in a virtual environment (VE). The software was developed using the Unity game engine.

Most of the IVAR system components are wired, making this setup unsuitable for interaction where the user needs to stand up and walk around and it lacks positional tracking. However, the setup works for use cases that involve a seated user (Figure 17). For this reason, it was decided to implement a VE based on a smart living room scenario in which the user, sitting on a chair, can interact with a set of consumer electronic devices.

IVAR is capable of simulating technologies that are not yet developed and of simulating the registration and tracking of virtual objects such as a text description popping up in front of the TV. It is also easy and inexpensive to add more virtual devices such as a TV, tablets and a wristband. It is different from the WozARd in that it does not rely on a human operator; the user interacts as he or she wishes. However, the method has the disadvantage of being static, since users need to sit down and their movements are somewhat limited because they are connected to a computer with cables (Figure 17). See Paper 2 for more details.

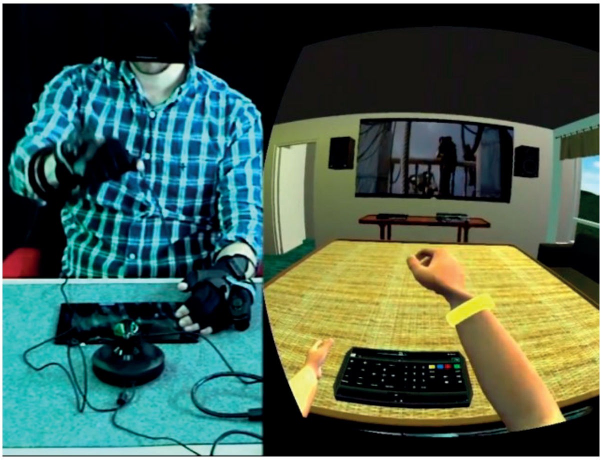


**Figure 17.** IVAR in use.

**VRUbi** is the second VR-based prototyping tool developed in this thesis and is a combination of both WOZ and VR technology based on room-scale tracking. The software was developed using the Unity game engine and the hardware was the HTC Vive. A smart home environment was built with virtual smart devices (Figure 18). Commonly used smart devices such as lamps and a TV were integrated and smart plants were also added. The smart plants showed their water status on the user's virtual smartwatch. Since the HTC Vive offers room-scale tracking and embodied interaction, traditional switchers were placed on the wall where the user had to walk forward to turn the lights on or off. The traditional switchers were compared with other interaction models. For example, another way to control the lights and the TV was by pointing at the devices, and a third way was a combination of gaze and voice. The third way was used together with a wizard. VRUbi offered embodied interaction and it was easy to add smart things that are not so smart yet in real life. See Paper 3 for more details.

**Figure 18.** VRUbi in use.

## Interaction models

The interaction models developed in the course of this thesis are presented in this section. They explore a combination of explicit and implicit interactions. Wearables are used to perform simple tasks and to facilitate IoT interaction with IoT systems. Four basic tasks that a user of an IoT system needs to be able to perform are: 1) discover devices, 2) select a particular device, 3) view the device's status, and 4) control the device (Ledo, Greenberg, Marquardt, & Boring, 2015).

In an attempt to address the four basic tasks, four IoT interaction models were developed: UbiCompass, Floating Icons, World in Miniature, and Floating Menu.

### UbiCompass

The UbiCompass concept addresses the four Ledo et al. (2015) tasks by using a compass metaphor in combination with traditional touch interaction in the watch prototype (Figure 19). The idea behind UbiCompass was to offer at-a-glance discoverability, that is, telling the user where and what things are available, and simple interactions such as being able to turn things on/off quickly.

An early decision in the UbiCompass project was to use existing off-the-shelf standard components available for smart homes. The connected devices use the Z-Wave standard: a widespread standard found in plenty of third-party devices that are easily available and relatively affordable. The controlling communication runs through the network via a Wi-Fi router. The UbiCompass watch face prototype was developed in Android Studio for the Sony Smartwatch 3.

The strength of the design is in discoverability and controlling a device for simple interaction. It is easy to discover connected devices since they are illustrated as part of the watch face. This results in information available for a user to quickly get an idea of how many connected devices are available and their approximate whereabouts. Selecting a device requires a physical movement and can be awkward in some situations, in particular if the device you want to control is behind you. To see the status of the device, the user has to first point and then select the desired device.

The UbiCompass concept expressed in the prototype has several limitations including, positioning, the positions of the devices are coded in the name when connecting to its hub. The user's position is not tracked either. Consequently, the prototype only works within a limited area. See Paper 4 for more details.

**Figure 19.** UbiCompass watch face.

## Floating Icons

Floating Icons (Figure 20a) is one of three interaction models presented in Paper 5. It was developed using the Microsoft HoloLens, the Unity game engine, and Microsoft Visual Studio. The idea of this interaction model is built on having interactive holographic icons placed in proximity to the device it represents. When the user's head is directed at an icon, the icon changes color, informing the user that actions can be performed on that icon (Figure 20a). However, in this iteration, only simple interactions are offered to the user, such as turning connected devices on or off.

The strength of the design is the status. For example, the connected device status is visible by looking at it, and to control the devices, a mid-air tap is needed. The discoverability is relatively low since it requires the user to move his or her head around the room.

## World in Miniature

The World in Miniature (WIM) model (Figure 20b) is also one of three interaction models presented in Paper 5. It was developed using the Microsoft HoloLens, the Unity game engine, and Microsoft Visual Studio. The WIM model is built on the idea that the environment in which a user wants to control IoT devices has been modeled as an interactive hologram, complete with icons at appropriate locations.

The WIM model is inspired by the notion of a miniature "god's" eye view model that originally was developed by Furness (1986). A model of the user's environment is shown, embedded within the full-scale environment viewed on a head-worn display. Stoakley et al. (1995) expanded the idea to create a miniature model of the user's environment: a world in miniature (WIM). However, both of the above examples present WIM in a virtual environment. It was Bell et al. (2002) who introduced an AR exocentric WIM model, which provides the user an overview of the surrounding environment and the ability to discover, select and inquire about objects that may be directly visible to the user. A WIM model of one's close proximity or room is an efficient way to gather all added information from the system in a limited area, which possibly limits distraction issues.

What differs our WIM model from the above, is the ability to scale it: the user can choose to make it smaller or bigger. It is also possible to rotate the WIM model and place it in a fixed position or choose to have it "floating" in front of you. The functionality of the icons in the WIM model is the same as for the Floating Icons model.

The strength of the design is discoverability, the status of the connected devices, and the ability to control devices at least for simple interaction.

## Floating Menu

The Floating Menu model (Figure 20c) is also one of three interaction models presented in Paper 5. It was developed using the Microsoft HoloLens, the Unity game engine and Microsoft Visual Studio. The Floating Menu model was designed to reproduce a more traditional approach to IoT interaction. Since the development was carried out in the HoloLens environment, it was designed to resemble the Windows 10 operative system. An important difference compared with the Floating Icons model is that the Floating Menu follows the user's head movements so that the user does not lose the menu if he or she moves around or looks in a different direction.

The strength of the design is the status of connected devices and being able to control devices for at least for simple interaction. Discoverability was low since there is no connection between what you can use and where the devices are located. Selecting a device to control requires the user going through the icons in the menu.

Limitations regarding the Floating Icons, WIM and the Floating Menu are mainly related to the Microsoft HoloLens hardware and its software. The HoloLens comes with a number of limitations. One issue is the field of view. The HoloLens has a very small field of view, which leaves the user with quite a limited part of the screen in which he or she can interact with holograms. Another problem is the limited set of available hand gestures.

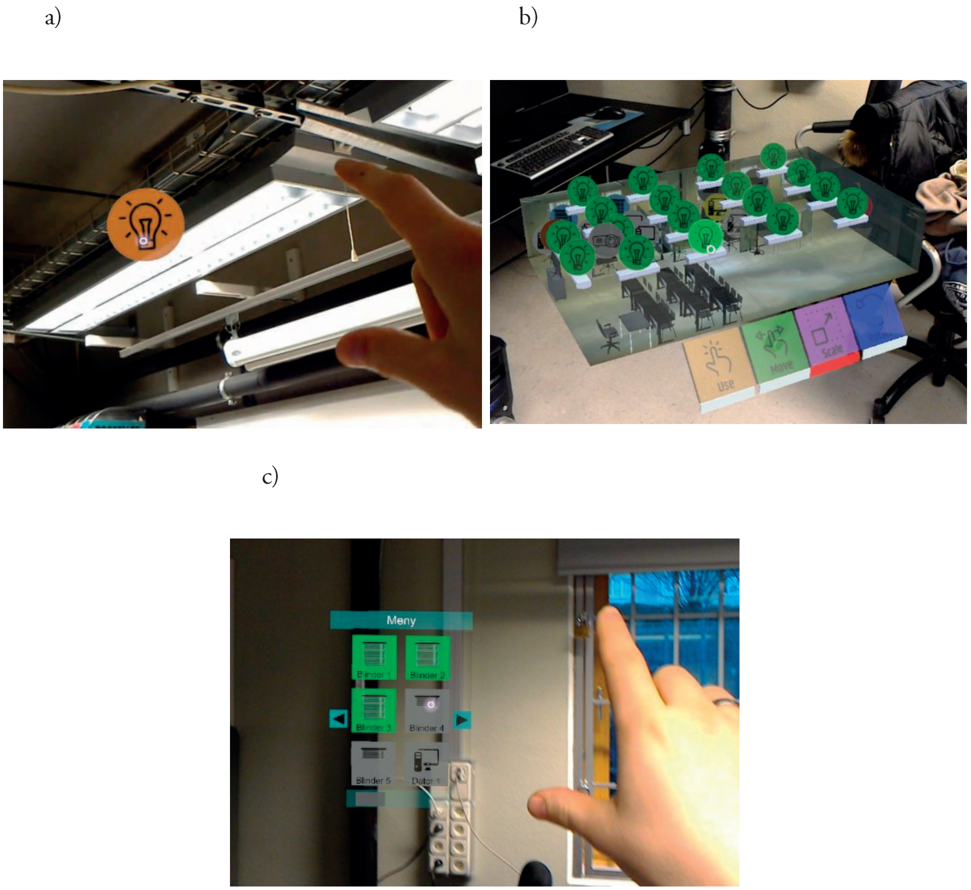
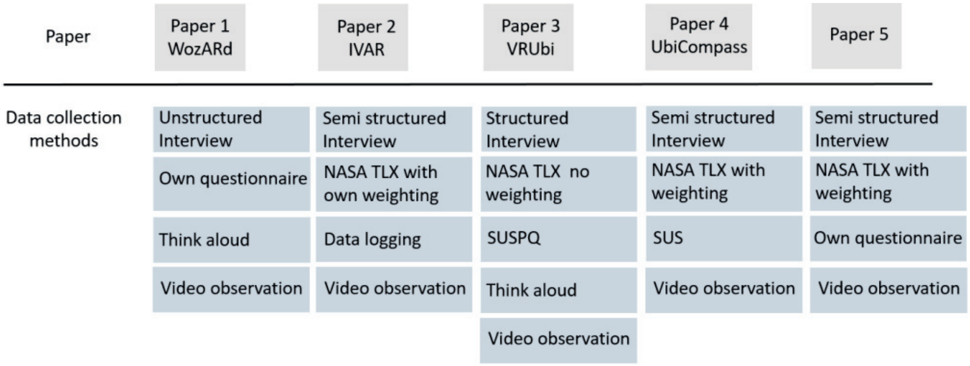


**Figure 20.** a) Floating Icons, b) World in Miniature, c) Floating Menu.

# Methods used for data gathering

This section describes the data gathering methods used when conducting user studies, followed by a description of the participants.



| Paper | Paper 1 WozARd | Paper 2 IVAR | Paper 3 VRUbi | Paper 4 UbiCompass | Paper 5 |
|---|---|---|---|---|---|
| Data collection methods | Unstructured Interview | Semi structured Interview | Structured Interview | Semi structured Interview | Semi structured Interview |
| | Own questionnaire | NASA TLX with own weighting | NASA TLX no weighting | NASA TLX with weighting | NASA TLX with weighting |
| | Think aloud | Data logging | SUSPQ | SUS | Own questionnaire |
| | Video observation | Video observation | Think aloud | Video observation | Video observation |
| | | | Video observation | | |

**Figure 21.** Summary of the methods used in each paper.

## Methods

Different research methods were used for the different experiments including quantitative and qualitative methods. Most of the thesis research was carried out using a different set of questionnaires for quantitative data, and different interview techniques for the qualitative data. Observation and think aloud were also used (Figure 21).

### Questionnaires

Questionnaires are a well-established technique for collecting demographic data and users' opinions. They are similar to interviews in that they can have closed or open questions (Rogers et al., 2011). Efforts are needed to ensure that questions are clearly worded and the data collected can be analyzed efficiently. Consequently, well-established questionnaires were used such as the NASA Task Load Index (NASA TLX), the System Usability Scale (SUS) and the Slater-Usoh-Steed Presence Questionnaire (SUSPQ).

**NASA TLX** is used to measure the perceived workload for specific tasks. It uses an ordinal scale on six subscales (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration). A second part of the NASA TLX creates an individual weighting of the subscales by letting the subjects compare them pairwise based on their perceived importance (Hart, 2006). There are different theories about whether or not to use the second part of the NASA TLX. That is why we tried different approaches. In Papers 4 and 5, the participants did the weighting individually, in Paper 2 we did our own weighting and in Paper 3, the participants only did the first part of the NASA TLX.

**SUS** is used to measure cognitive attributes such as learnability and perceived ease of use. SUS is often used to get a rapid usability evaluation of a system's human interaction (Brooke, 1996).

**SUSPQ** is used to measure the presence a user experiences in a VE (Usoh, Catena, Arman, & Slater, 2000). It was used in Paper 3. By presence, we mean how realistically the user will respond to the VE. For example, the feeling of being there (place illusion) and the illusion that the scenario being depicted is actually occurring (plausibility illusion) (Slater, 2009).

We also designed our own questionnaire for the experiment in Papers 1 and 5. Both of them were inspired by the SUS questionnaire but with additional questions for the specific experiments.

### Interviews

There are four types of interviews: unstructured, structured, semi-structured, and group (Frey & Fontana, 1994). If the goal is to gain first impressions about how users react to a new design idea, then an informal, unstructured interview is often the best approach. But if the goal is to get feedback about a particular design feature, such as the layout of a new web browser, then a structured interview or questionnaire is often better (Rogers et al., 2011). In the experiment described in Paper 1, unstructured interviews were conducted, since it was an early stage and the goal was to get the first impressions about how users react to the combination of a HWD with a watch as an input device. For the experiments described in Papers 2, 4, and 5, semi-structured interviews were conducted. One part of the interview was structured since we wanted to pinpoint specific attributes; the other part was more open and explorative. The interviews in Paper 3 were structured with a predefined list of questions because the prototyped smart home was in a more mature stage.

## Concurrent think aloud

Concurrent think aloud (CTA) is one of the most direct and widely used methods to gain information about participants' internal states (Ericsson & Simon, 1980). CTA is a standard procedure in the field of usability testing that is considered to be both reliable and cost efficient (Barnum, 2010; Nielsen & Pernice, 2009). The CTA method was used in the experiments described in Papers 1 and 3. In Paper 1, the method had two purposes: to gain information on the participants' experience when attending to the information, and to aid the human operator in understanding if the participants were experiencing any problems. However, very few participants actually said anything during the city tour since they probably were focused on the task of following the instructions given from the "system." In Paper 3, CTA was used during the low-fidelity interaction experiment as an initial explorative step. The method had one purpose and that was to understand what the participants tried to do during their imaginary interaction.

## Observation

Observation is a useful and relatively low-cost data gathering technique, albeit analyzing the data is more demanding. It can also be used at any stage during product development. Observations conducted later in development, for instance in an evaluation, may be used to investigate how well the developing prototype supports the tasks and goals. Users may be observed directly by the investigator as they perform their activities, or indirectly through records of the activity (Rogers et al., 2011). In the experiment described in Papers 1 and 5, indirect observations of the recorded videos were performed; in the experiment described in Papers 2, 3 and 4, direct observations were performed. However, observation was not used as the primary method; questionnaires and interviews were used for that purpose. Hence, no strict observation protocols were established in the studies and only simple notes were taken and analyzed.

Video observations were used in all experiments. For the experiment described in Paper 1, all test sessions were recorded and fully transcribed. Each participant's video recordings were analyzed; individual quotes, actions, and behaviors were categorized and labeled. From the experiment described in Papers 2 and 4, the participant's comments from the semi-structured interviews were transcribed and analyzed. The videos from the experiments in Papers 3 and 5 was not transcribed but used as observations.

### Statistics

The quantitative data of Paper 2 were analyzed using the Wilcoxon Signed Rank Test for two paired samples to find out whether there were any significant differences in the NASA TLX between the proposed interaction concepts. In Paper 3, ANOVA between the interaction models was used to find statistical differences for the NASA TLX scores. In Paper 4, paired t-tests were used to see if there were any significant differences for the NASA TLX and SUS scores between the suggested IoT UbiCompass prototype and the mobile application. In Paper 5, a mixed ANOVA was used, since two different groups of participants tested three different interaction models with the variation of the icon density. Moreover, the Friedman test was used to detect significant differences for the NASA TLX across the groups.

## Participants

The participants for the experiment described in Paper 1 consisted mainly of students with no engineering background except for one. 21 participants (6 females and 15 males, *M* = 26.2, *SD* = 14.17) were recruited.

Participants for the experiments described in Paper 2 were mainly recruited from university students. 24 participants (9 females and 15 males, *M* = 24.5, *SD* = 5.43) participated in the device discovery part. 20 participants (9 females and 11 males, *M* = 23.8, *SD* = 5.06) participated in the device interaction portion. The device interaction participants were a subset of the device discovery group (due to technical problems, 4 out of the original 24 participants' data could not be used). The participants were mainly students with an engineering background.

Participants for the experiment described in Paper 3 were recruited by notifications on Facebook and through advertisements on public billboards at university faculties and cafés. In total, 21 participants were recruited. The participants consisted of twelve males and nine females, were between 19 and 61 years old (*M* = 26.5, *SD* = 11.91) and from various backgrounds (although 16 of them were students at the university).

Personal social networking was used to recruit participants for the experiment described in Paper 4, half with non-technical backgrounds to see if not-so-tech-savvy participants would be able to manage the given tasks. In total, 36 participants (18 females, 18 males) were recruited. Friends and family members were excluded. The age of the participants ranged from 18 to 51 years (*M* = 30.8, *SD* = 9.39). The group was composed of 18 participants with an engineering background and 18 participants with a non-technical background.

Participants for the experiment described in Paper 5 were enrolled in university, with the majority being students from the faculty of engineering. They were divided into two groups according to a predetermined randomized order with reservation for adjusting the gender balance at the end if needed (was not needed). Group 1 had 10 participants (3 females), mean age 24.3 years (*SD* = 3.40). Group 2 had 10 participants (2 females), mean age 24.0 years (*SD* = 1.05). In total, 20 participants were recruited.

# Paper Summaries

The papers are briefly described in this section. Table 1 shows an overview including purpose and take aways from each paper.

**Table 1.** Summary of purposes of the presented papers, questions that were asked, methods that were used and the take aways.

| | Purpose | Question | Methods | Take away |
|---|---|---|---|---|
| **Paper 1** | Introduce and evaluate the capability of the WozARd method to simulate a believable illusion of a real working AR city tour. | Can WozARd be used as a prototyping tool for AR interaction? | 1.Unstructured interview<br>2. Own questionnaire, inspired by SUS<br>3. Think aloud<br>4. Video observation | The WozARd method worked reasonably well in the way it was used in this study. The two most important factors are the design of the wizard device and the skill of the human operator. |
| **Paper 2** | Introduce and evaluate IVAR, a VR based prototyping tool for exploring the design space of AR and IoT interaction using a virtual environment. | Can VR be used to explore AR interaction? | 1. Semi-structured interview<br>2. NASA TLX with own weighting<br>3. Data logging<br>4. Video observation | IVAR shows potential to become a useful prototyping method. However, tracking technology needs to improve, both with regards to intrusiveness and precision. |
| **Paper 3** | Introduce and evaluate the VR technology based on room-scale tracking, to prototype IoT interaction. The tool is called VRUbi. | Can VR be used to explore IoT interaction? | 1. Structured interview<br>2. NASA TLX without weighting<br>3. SUSPQ<br>4. Think aloud<br>5. Video observation | VR has a potential to become a useful prototyping tool for IoT interaction. |
| **Paper 4** | To introduce UbiCompass concept and to compare a functional, smartwatch prototype of it with a commercial mobile application when using an IoT solution. | How does the UbiCompass concept work compared with traditional mobile applications? | 1. Semi-structured interview<br>2. NASA TLX with individual weighting<br>3. SUS<br>4. Video observation | UbiCompass works compellingly for accessing information at-a-glance and for simple interaction. |
| **Paper 5** | To introduce and compare three basic interaction models for HWD-based AR, with a focus on the discovery and selection of IoT devices. | What are the pros and cons of three basic models for IoT interaction using glasses-based AR? | 1. Semi-structured interview<br>2. NASA TLX with individual weighting<br>3. Own questionnaire<br>4. Video observation | With few devices to control, the models did not cause significantly different interactions. However, with many devices to engage with, the WIM model stood out as especially difficult and time-consuming. |

## Paper 1: WozARd: A Wizard of Oz Method for Wearable Augmented Reality Interaction – A Pilot Study

This paper presents an initial investigation of the capability of the WozARd tool to simulate a believable illusion of a real working AR city tour. Aspects mainly concerning the method itself were studied but also the limitations of current hardware were considered since they contribute to the participants' experience. A pilot study was carried out in which qualitative and quantitative data was collected and analyzed from 21 participants who performed a predefined city tour using the WozARd on wearable technology. The data analysis focused on seven categories that potentially can have an impact on how the WozARd method is perceived by participants: precision, relevance, responsiveness, technical stability, visual fidelity, general user experience, and human operator performance. Overall, the results seem to indicate that the participants perceived the simulated AR city tour as a relatively realistic experience despite a certain degree of technical instability and human operator mistakes. Their subjective experience of the simulated AR city tour, as measured by the questionnaire, was overall positive and in general, the city tour seemed to induce a feeling of a real, autonomous system rather than a system being controlled by someone else. The observation data seemed to confirm this. All participants managed to accomplish the AR city tour and in general, they seemed to enjoy walking the simulated AR experience. Based on the experiences of this study, the authors believe that two of the most important factors contributing to these results are the design of the wizard device of the WozARd tool and the skill of the human operator.

In conclusion, the WozARd method seemed to work reasonably well at least in this specific use case. In this study, only one specific use case for wearable AR was simulated. No real claims about the general usefulness of the WozARd method in a design process can thus be made based on the presented data.

## Paper 2: A Prototyping Method to Simulate Wearable Augmented Reality Interaction in a Virtual Environment – A Pilot Study

In this paper, a proposed VR-based prototyping tool called IVAR (Immersive Virtual AR) for prototyping wearable AR and IoT interaction in a virtual environment (VE) is presented. IVAR was developed in an iterative design process that resulted in a testable setup in terms of hardware and software. Additionally, a basic pilot experiment with 24 participants was conducted to explore what it means to collect quantitative and qualitative data with the proposed prototyping method. The main contribution is that IVAR shows potential to become a useful wearable AR prototyping tool, but that several challenges remain before meaningful data can be produced in controlled experiments. In particular, tracking technology needs to improve, both with regards to intrusiveness and precision.

## Paper 3: Using VR as Prototyping Tool for IoT Interaction in a Smart Home Environment

This paper presents a proposed VR-based prototyping tool referred to as VRUbi. VRUbi uses VR technology based on room-scale tracking to prototype IoT interaction. In order to choose appropriate types and modes of interaction, six participants were selected for a pilot study. The participants were invited to a real but small living room where they were asked to imagine a variety of day-to-day objects as being hyper-intelligent and connected to the Internet. They were then asked to freely “interact” with these objects. Although the interaction was completely imaginary and performed without any type of feedback, this highly explorative test lead to very useful findings. The test persons showed similar preferences concerning interaction modalities such as voice and gestures. Based on the findings from the pilot study, three IoT interaction concepts were developed in VR, and then compared in a controlled experiment with 21 test persons for evaluation and comparison. Some statistically significant differences for the NASA TLX score and subjective preferences could be observed in the quantitative and qualitative data, respectively. This shows that VR has a potential to become a useful prototyping tool for IoT interaction.

## Paper 4: UbiCompass: An IoT Interaction Concept

This paper presents a novel IoT interaction concept called UbiCompass. A functional, smartwatch face prototype of the UbiCompass was developed and integrated with an existing smart home system. Wearables have the potential to enable at-a-glance access to information and can continually sense the surrounding environment. We thus emphasized the watch form factor attributes and put our efforts into achieving simplicity and easy access. The UbiCompass user interface was then compared to a traditional smartphone mobile application user interface in a controlled experiment with 36 participants. We wanted to find not-so-tech-savvy users, so social networking was used and we managed to get half of the participants with no engineering background.

# Paper 5: AR as a User Interface for The Internet of Things – Comparing Three Interaction Models

The purpose of this paper was to compare three basic AR interaction models for the HWD form factor. The focus was on discovering and selecting devices implemented for Microsoft HoloLens. An experimental study with 20 participants was conducted. They were split into two groups: one with low device density and one with high device density. Each group had to solve the same task using each of the three interaction models.

The results showed that with few devices to handle, the participants' interactions did not differ significantly. However, with many devices to engage with, the World in Miniature model stood out as especially demanding and time consuming. There was also high variability in term so which model the participants preferred by, possibly implying that a combination of the three proposed models is desirable in a fully developed AR system for managing IoT devices.

# Discussion

This section discusses different aspects of the prototyping tools and the strengths and weaknesses of the interaction models used for IoT interaction. Methodological issues and future opportunities are also discussed.

## Prototyping methods

In general, the results of the research presented in this thesis suggest that the three prototyping tools – WozARd (Paper 1), IVAR (Paper 2) and VRUbi (Paper 3) – are suitable for exploring IoT interaction. The first tool, WozARd, is dependent on a human wizard and the other two are based on VR technology. But why do we put this effort into developing tools to fake an experience and why do we use VR technology? Why not just prototype real devices in the real world directly?

Let us start with why we put so much effort into faking an experience. Much of this has to do with the attributes of cost, timeliness, and disposability (Buxton, 2010). Designing an interactive system typically involves an iterative process of brainstorming, prototyping, development, user testing, and evaluation (Dow et al., 2005). This is not a clear-cut process; it often iterates through many cycles before reaching a final system. There are three important roles that prototypes play: filtering out early strategic decisions and in so doing, avoid having to make them during the development phase; emphasizing certain attributes, features or dimensions; providing conceptual and reflective guidance (Lim, Stolterman, & Tenenberg, 2008). Moreover, we need to keep in mind that we are prototyping for IoT environments where potentially everything could be connected, although that is not yet the case. As already mentioned, getting data from users early in a project helps developers make better decisions about whether to continue with a certain concept or try a different one. In order to get as accurate data as possible, we fake experiences so that the prototype the user tests feels as close as possible to a real working system. By letting the user interact with real devices instead of paper prototypes, for instance, increases the fidelity. It was apparent that although a human wizard was there during the tests in the WozARd case, the participants focused on the devices that they were interacting with and paid very little or no attention to the wizard.

So why VR technology? For the same relevant attributes as mentioned above: cost, timeliness, and disposability. Imagine having several connected IoT devices such as TV screens in different sizes that are costly and take up space. When a study is finished, you would have to dispose of them somehow, not just throw them away; but in a VR environment, you can create TV sets in different sizes and numbers at almost no cost and that take up no physical space. Moreover, many IoT sensors and connected devices are not mature enough and are still under development. With VR technology, you can simulate different maturity levels of the sensors; you can simulate different scenarios and environments in the office space or at home, with lots of virtually connected devices or just a few. You can even create environments that do not yet exist. Another reason that emerged during the research is the fast evolvement of VR technology. In the experiment presented in Paper 2 for instance, the participants were required to sit on a chair when interacting because they were connected to lots of cables to track their hand movements. As a result, the scenario was intentionally designed so that the participants were sitting in a living room with a virtual and a real table placed in front of them to get the feeling of an enhanced presence. The HWD, which had low resolution, was the first developer version that Oculus had on the market back then. One could wonder if any results could have emerged from this clumsy setup and environment. The results that did emerge suggested that the setup had potential, and the one thing we found to be most significant was the enormous need for better tracking. When VR technology with room-scale tracking became available, we had a similar motivation and conducted a new study but with improved tracking. As theory suggests, the more immersive participant experience that resulted from using the newer improved VR technology was capable of inducing a higher degree of presence (Cummings & Bailenson, 2016). This was noticeable in the Paper 3 results. The new setup offered much higher resolution on the HWD, and better tracking resulting in a more embodied experience.

Even if it had not been confirmed in detail in the thesis research, the use of VR as a prototyping tool is time efficient, since many test sessions can be performed with different environmental setups in a relatively short time, compared to doing it in the real world. However, the experience of a virtual environment will never be as realistic as experiencing the real world, at least not with the current technology in which only a few of the human senses are stimulated: vision, hearing and partly tactile. The current focus is on vision. Audio is getting more attention, though, in such products that support HRTF (head-related transfer function), and 3D audio rendering algorithms are becoming available. HRTF can be used for several things, such as to simulate different environments since the HRTF describes how a sound from a specific point will arrive at the ear and orient the user in the right direction he or she should look.

Nevertheless, one important takeaway for organizations that develop IoT systems or services is to use VR to simulate different scenarios and interactions.

## Ability to design and explore user interfaces

Some of the research results presented look promising for each prototyping tool, but let us dive into each tools' ability to design and explore user interfaces. There are different ways to distinguish the prototyping tool's ability to do this. One way, according to Lim et al. (2008), is to distinguish the tool's ability in different activities in the design process. Another way is to distinguish their ability as Liddle (1996) does by focusing on the user interface perspective and distinguishing between three different abilities: 1) graphical design, 2) interaction, and 3) conceptual model.

Graphical design deals with what appears on the user's screen. All three tools are suitable for prototyping and evaluating a graphical design. WozARd has the advantage of being able to run on all Android form factors including smartphones, tablets, TVs, and Android-based glasses (e.g., Epson or Google Glass). Moreover, it is possible to add images of graphical user interfaces or an image of a sketch without recompiling the code. However, WozARd does not support 3D models and more importantly, it does not support tracking. Thus, it cannot be used for graphical user interfaces that need to be correctly registered in a 3D space. On the other hand, both IVAR and VRUbi are suitable for graphical user interfaces that need to present 3D models and graphics that have to be correctly registered in a 3D space. Keep in mind though, that each change of the 3D model or the graphical image requires a recompilation of the code, and they only work on HWDs. If the intention of the study is to focus only on the graphical design, paper prototypes should also be considered. They are faster and cheaper, but of course not as realistic as the presented tools.

The second ability, interaction, is about the control mechanism or the input method to control the commands. Interaction can be prototyped and evaluated with all three methods. WozARd lets the user make small gestures on small areas such as the smartwatch display; the human wizard can understand speech and gesture interaction, but it requires a trained wizard who can interpret and react to user behaviors and actions in a fast and correct manner. The two VR methods, on the other hand, use VR technology to simulate the environment in which participants test the interaction. The test cases in IVAR were run in a controlled manner without relying on a human operator. However, the devices used for input in IVAR were relatively cumbersome with several tracking and mobile devices attached to the user, resulting in a tangle of cables and straps. This probably had a negative effect on the user's sense of presence and precision. The test cases in VRUbi were run in a controlled manner without relying on a human operator, but VRUbi can also run test cases that involve speech and/or head direction as interaction. In that case, it would use WOZ and rely on a human operator. Another input mechanism used in this method is the HTC Vive hand controller. Despite the hardware design, the participants quickly accepted the hand controls as a replacement for their own hands. VRUbi also offers embodied interaction with the help of room-scale tracking, which means the user can walk around in a limited area of about nine $m^2$. However, to simulate larger IoT environments, such as parks, squares or entire buildings, some sort of locomotion technique needs to be used, which in turn might break the sense of presence. WozARd on the other hand, has the benefit of not being constrained to a limited area; you can be and walk anywhere but you have to be there physically, and as already mentioned, it does not have the tracking functionality implemented.

The third ability, which is the most important component to design properly according to Liddle (1996), is the system's conceptual model. Everything else should be subordinated to making that model clear, obvious and substantial. VR-based prototyping is more suitable for prototyping and evaluating advanced conceptual models because it offers sub-millimeter tracking of the user and embodied interaction. Real-world prototyping with WOZ and its ability to design conceptual models is dependent on tracking. For instance, if the same experiments in Papers 2 and 3 were prototyped with WOZ, there would have been a problem with latency. Since the human wizard would need to carefully observe what the user was pointing at and quickly try to press the correct button to show the correct image, there was a risk that by then too much time would have elapsed and the user would have already moved to the next device. The results of Papers 1 and 2 suggested and predicted that better tracking would offer a more realistic experience for the user and that we would probably see more statistically significant differences of the results gathered from the user studies, which the results in Paper 3 indeed showed.

## Fidelity level of the tools and for whom?

Another important aspect is the role of the prototype's fidelity level in the design process. Its role is to facilitate the exploration of a design space and uncover relevant information about users and their work practices by giving more details than a sketch, and being testable. One should remember that prototypes are useful for communicating an idea between designers, engineers, managers, and users (Buxton, 2010). They also permit early evaluation since they can be tested in various ways, including traditional usability studies and informal user feedback throughout the design process. Based on the research results, I am convinced that WozARd can be used as a low/mid-fidelity prototyping tool (Figure 13), since as a designer you can sketch an idea, take a photo of the sketch and use it without any recompilation of the code. In addition, it has the strength of being flexible, mobile, and able to test user interfaces in different form factors, but it does not facilitate high-fidelity AR prototyping due to the lack of tracking functionality and that it relies on the human wizard. Carter et al. (2008) present similar findings showing that WOZ prototypes are excellent for early lab studies but do not scale to longitudinal deployment because of the labor commitment for human-in-the-loop systems. Nevertheless, another strength that is worth mentioning is that WozARd has the potential of to be used by a broader "audience" because people with less technical backgrounds can also use it. It does not require any programming skills, but it is an advantage to be able to handle Windows File Explorer.

Both IVAR and VRUbi are suitable to use as a mid/high-fidelity prototyping tool. This is because they can provide three-dimensional visualizations of more complex devices and can simulate more complex scenarios and the registration and tracking of virtual objects; in particular when using VRUbi since it has better tracking, better field of view, better display resolution and the possibility to sit or walk around a smaller room. However, both require a person with technical background to setup a new simulation or to make changes in the current simulation.

## Interaction models

Getting users to understand the interaction model is challenging. According to Norman (2004), the secret to good understanding is to establish a proper conceptual model. In an ideal world, the mental model in the head of the designer and the mental model in the head of the person using the device should be identical. In general, the research results indicate that all participants seem to have understood the conceptual models presented in this thesis. Once they grasped how the interaction models worked, they had no problems solving the tasks. Moreover, they showed signs of enjoying the interaction models as determined by post-test interviews and spontaneous positive comments during the testing.

The presented user interfaces used for IoT interaction utilize two form factors: a smartwatch and an HWD. UbiCompass, which is described in Paper 4, was built for the smartwatch form factor while Floating Icons, WIM and Floating Menu, which are described in Paper 5, were built for the HWD form factor.

The main strength of the UbiCompass concept is that it truly exploits the characteristics of a wrist-worn wearable device (Mann, 1998b). First, by making the icons that illustrate the connected devices part of the watch face and not as a separate application that needs to be started to run. This results in information that is always available or in a sense always “on”. Second, the information is available at a glance, which means that a user can quickly get an idea of how many connected devices are available and their approximate whereabouts. UbiCompass running on a smartwatch form factor comes with several limitations as well. In our experiment, for instance, we only had five connected devices, but if we had scaled up the number of connected devices with the current design, it would have cluttered the watch face due to the limited “screen real estate.”

The notion of the three interaction models developed for the Microsoft HoloLens, an HWD form factor, has several similarities to the UbiCompass concept. They both focus on the aspects of discovering and selecting connected devices, and that the user interface should automatically appear when a person enters a smart office, for example (i.e., the user does not have to start up the application). Although HoloLens is a developer product, it shows the benefit of using AR as a user interface for IoT interaction. The WIM model has good discoverability since the participants are able see an overview of the whole room. The Floating Menu has low discoverability since there is no connection between what you can use and where the devices are located; you may also need to browse through the menu to find a specific device.

But why should we use the UbiCompass or the proposed interaction models with an HWD? Why not just put a digital assistant device like Alexa or Google Home in the room? There are several reasons. For example, speech interaction in general is unable to discover what you can interact with and is unable to make all possible actions visible to the user. You could perhaps ask Alexa or Google Home, but you might have trouble remembering what was listed and what the different devices were called. Moreover, as pointed out by Norman & Nielsen (2010), natural user interfaces built on gestures and speech interaction lack several fundamental principles of interaction design. These are principles that are completely independent of technology, such as visibility (affordances or signifiers), feedback, consistency, non-destructed operation (undo), discoverability, scalability and reliability (Norman & Nielsen, 2010). This is, of course, less of a problem in a familiar home environment, where the user knows what devices and services are available, and where they are located. However, in an unknown environment, such as a new workplace, it could be difficult for a user to discover nearby devices and their capabilities.

## How close to real products are we?

Based on the research results, it is tempting to think of UbiCompass as a low hanging fruit in the sense that it is easier to move from research to product then the AR interaction models that run on the HoloLens. This is because our prototype is based on off-the-shelf products and is running, albeit the user needs to manually update the device position in our solution. In order to make a product that can dynamically update and add connected devices and their positions automatically, we need to add a universal middleware solution that supports and can track all devices. Several attempts have been made and several open source projects are ongoing including openHAB and HomeAssistant. To track each device, indoor positioning needs to be in place with enough accuracy to be able to separate devices in a room.

What about the HWD solution? The Microsoft HoloLens is still a developer version and it should not come as a surprise that wearing a smartwatch is more socially acceptable then wearing an HWD. HWDs are currently too bulky and create an invisible distance from the people around you. Moreover, HWDs are perceived as if they isolate the user from others. Another reason is, of course, privacy issues. Users of

HWDs could surreptitiously monitor many people at any time (Hong, 2013). Looking back in history, parallels can be drawn when the first cameras by Kodak in the late 19th century made it possible to take photographs in "just" several seconds. For a time, Kodak cameras were banned from the Washington Monument in the U.S. (Hong, 2013). In the same manner, people who wear Google Glass were banned in some restaurants (Levy, 2014). Other examples are, when the first headphones arrived in the 80s, or when the first small mobile phones came in the late 90s, and when the camera was integrated around 2004. Everyone thought they were clumsy, ugly and privacy invasive. However, people got used to them. Now, headphones are trendy and most people own smartphones with an embedded camera. In a similar manner, when HWDs will start to look like normal glasses and will be available as lenses, we will be able to experience the full potential that AR can offer. As with smartphones, people will get used to seeing others who are wearing head-worn displays and these will start to reach a wider audience.

### For whom are the interaction models intended?

The first two questions one should ask before starting to develop interaction models are: Who are the users? What is the problem to be solved? In the thesis introduction, I stated that the user was not so tech savvy, and the problem to solve was how that person could discover and directly interact with the numerous connected things predicted by the IoT vision. Focusing on not-so-tech-savvy people does not exclude the tech-savvy ones; on the contrary. So, how do we know if the interaction models met the goal? Of course, there is no simple answer but we tried to address it by mixing the not-so-tech-savvy and the tech-savvy participants. We also used questionnaires that tried to pinpoint cognitive attributes and perceived workloads. Based on the results the interaction models seemed to work, at least on the participants who tried them.

What about people with impairments? The proposed interaction models could help people with mobility impairments to control devices remotely. However, people with cognitive disabilities may very well find them too complex.

## Methodological issues

As in most emerging technological fields, AR researchers and developers have had to solve many technical issues to create usable AR applications, such as developing tracking and display systems, authoring tools, and input devices (Dünser & Billinghurst, 2011). As the field matures and more applications are developed, including the end users in the evaluation of these systems will become more important. So far, the number of AR systems formally evaluated is rather small (Dünser, Grasset, Seichter, & Billinghurst, 2007). No more than 8% of published AR research papers include formal evaluations (Dünser & Billinghurst, 2011). In order to bring the technology out of the research labs and into people's everyday lives evaluation testing is an important step. One reason why there are so few evaluated AR interfaces may be the lack of suitable methods for conducting such evaluations. Many authors agree that emerging interfaces, such as VR or AR, cannot rely solely on design guidelines for traditional user interfaces (Dünser & Billinghurst, 2011).

In this thesis research, five different evaluations were conducted but all five vary in their approaches. The two main intentions were to measure: 1) the perceived workload, and 2) the cognitive attributes such as learnability and perceived ease of use. Using NASA TLX is quite convenient for evaluating the perceived workload, because it is time effective, well supported by online tools, and well established. SUS is a commonly used questionnaire for measuring cognitive attributes. The main differences between the evaluations presented in this thesis were the way NASA TLX was used, or whether the second part of the NASA TLX was used or not. This second part is used to create an individual weighting of the subscales. Participants are asked to perform pair-wise comparisons of the subscales based on their perceived importance. This captures the participant's view of the relevance of each measurement with respect to perceived workload. However, according to Hart (2006), using the second part of NASA TLX may actually decrease experimental validity. For this reason, the first part is used most often by itself. There are different theories as to whether the second part should be used or not. We conducted NASA TLX in three different ways. In Paper 2, the authors did the weighting and used the same weighting for all users. In Papers 4 and 5, the participants did their own weighting. In Paper 3, we did not use weighting. Not using the second part is easier, but in this way, the participant's total perceived workload could be considered as being inaccurate. If one participant rated the physical subscale as being high but that it was not as important as the other subscales, it would give a more accurate value of the total perceived workload.

In all five studies, methodological triangulation was used to increase the quality of the data. Triangulation refers to the investigation of a phenomenon from (at least) two different perspectives (Rogers et al., 2011). Examples of methods we used in the evaluations included questionnaires, interviews, concurrent think aloud and observations.

Another aspect of the design of the evaluations is the high number of relatively young people in the studies. The participants were primarily male students. Having a better mixture of gender and age is preferable to gain a wider range of users' thoughts on the potential future of using other form factors than smartphones. The impact of having such an unbalanced gender mixture can result in designing products that generate unexpected negative consequences (Ely, 2015). Ely lists several examples of design solutions that had unexpected negative consequences for woman. These include seat belts and medications that are less safe for women, and offices temperatures that are too cold for women.

The results of the studies presented in this thesis show that the systems seem to work for relatively young people, but do not say anything about how they would work for older people. We are also unable to say anything about how the systems would work for people with cognitive and motor limitations.

## Future possibilities

This thesis touches upon four emerging technologies: IoT, AR, wearables and VR. There are many companies pushing these areas forward, such as Apple, Google, Microsoft and Amazon. In this section, we pose the following questions: How far can we take the prototyping tools? How will we interact in the future with IoT devices? Are there any problems to consider?

### How far can we take the prototyping tools?

The IoT, AR, wearables and VR technology are continuously improving at a fast pace regarding both the hardware and the software. At a certain point, we will have displays with the same resolution as the human eye. At least in theory, the ultimate display would be a consumer version of the virtual retinal display (VRD). The VRD has the potential to offer both a VR experience by blocking out the real world, and an AR experience since the virtual elements are rendered with lasers directly into the user's retina. If such a VRD becomes available, it will be harder to differentiate the real from the virtual.

3D sound is also improving. By making use of HRTF technology, we will be able to experience individually adapted 3D sound and simulate more acoustically correct sounds depending on the environment and the furniture in the virtual room (OSSIC, 2018).

The aim of products that can offer tactile feedback is to present haptic information by stimulating the user's tactile sense. Because human skin is highly sensitive, significantly less energy is required to produce a strong recognizable tactile sensation. Thus, the products are generally much smaller and more lightweight. Examples of tactile products are electrovibration displays, surface friction displays, and thermoelectric displays (LaViola Jr et al., 2017). They have all been built in research labs and are not commercially available yet. Haptic feedback can be simulated using an ultrasound-based in-air haptics display. More recently, HaptX's (2018) developed microfludic technologies based on air-channels and magnetic tracking. The air channels can simulate unique haptics and the magnetic tracking is a thousand times more accurate than HTC Vive tracking.

Including the sense of smell through olfactory stimuli is also important. In practical terms, scent is primarily used for smelling food or for detecting danger (like fire). The functions of taste and smell are aided by a large affective or emotional component. Things that are bad for us often taste or smell unpleasant, and things that are good for us generally taste or smell good. Olfactory cues associated with a past place or event can trigger memories, which in turn may generate emotional reactions (Goldstein, 2010). Moreover, how humans detect many scents varies widely, and complex scents are easier to remember.

In conclusion, we will be able to prototype very close to reality with multiple senses, but we need to ask ourselves if we need all senses to be very realistic? After all, with our basic setup of the VR-based prototyping tools, we have been able to collect valuable data and the participants seem to react in the virtual world as if they were in the real one. Perhaps it is even better to not have the experience seem too real. I share Buxton' (2010) recommendation to keep the level of details in sketches low (Buxton, 2010), and apply it to keeping the level of details in the VE low as well. The participant should feel that it is a relatively early prototype and that he or she should not feel bad about criticizing it or the suggested interaction. On the other hand, I think this depends on what type of data you are collecting. The level of detail can be lower if you want to get at what the user thinks about a certain interaction. However, if the purpose of the study is to collect data about the user's behavior or ability to interact in VR, a higher level of detail or higher fidelity and presence are needed.

## How will we interact in the future with IoT devices?

Poslad (2009) roughly divides IoT interactions into two types: implicit and explicit. Implicit interaction is built on Weiser's (1999) vision in which computation, communication and sensing would be enmeshed in the everyday world, for example by having sensors that monitor users and can automatically take action. Pure, explicit interaction is context free; it requires the user to actively take action every time something needs to be controlled. In contrast to Weiser, Rogers (2009) argues for a shift from implicit to explicit interaction, in order to encourage people to be proactive and decide what to interact with. I am convinced that future IoT systems will include both implicit and explicit interactions. In our interaction models, we have both. The implicit part is the idea of the device sensing when we enter a room, and it shows us a user interface without needing to start up an application. The explicit part is that the user has the ability needed to check what is available and control it. However, both implicit and explicit interaction types need different input modalities in order to discover, select, view status and control IoT devices. Examples of input modalities are speech, gesture and eye tracking.

Speech is a powerful approach to interact with IoT devices but as a complement together with another input device. When functioning properly, speech interaction can be a valuable tool, especially when both of the user's hand are occupied. Speech recognition has matured sufficiently to the point that the user can say the name of the speech recognition agent followed by the speech command. As already mentioned, though, it lacks fundamental interaction principals such as discoverability and visibility. Other obvious issues in using speech interaction is when the setting is crowded, when the noise level is high, or when one is supposed to be quiet like in a library or during class.

An alternative interaction modality is gestures. Gestures are a fundamental part of human communication; no need for designated input devices and they have the potential for high information bandwidth (Wigdor & Wixon, 2011). However, current VR and AR systems only allow relatively coarse gestures without the nuanced variation offered by finger gestures (e.g., pinch to zoom). Nevertheless, the Google Project called Soli (2015) enables very small discrete finger movements to control a user interface. I think using small gestures to interact with IoT devices is a much more comfortable and ergonomically better way to control a user interface.

Lately, most of the big companies working with AR and VR HWDs have turned their attention towards eye tracking. One can wonder why the sudden interest. Eye tracking opens up the opportunity to more accurately evaluate and investigate users' interests and cognitive workloads. Zagerman et al. (2016), for example, "encourage the use of eye tracking measurements to investigate users' cognitive load while interacting with a system." Eye tracking can also be used as an input method to control the user interface presented with AR or in the VR environment.

The future input modalities will most likely be a hybrid solution, combining speech, gestures and eye tracking, all of which will allow us to discretely interact with physical and digital things without thinking about a certain modality. In everyday life, we are able to perform physical actions and perceive information in the background or on the periphery of our attention. Similarly, we will be able to perceive and control digital information in the periphery of attention. Such peripheral interaction can support IoT technology to fluently embed itself and become a meaningful part of people's everyday routines (Bakker, Van Den Hoven, & Eggen, 2014). Moreover, the hybrid solution will work in symbiosis with fashionable wearables such as a smartwatches, jewelry, and clothes. I think that we will see an increase of smart clothes such as belts, shoes, and pants that will be able to collect data but also function as placeholders for the battery or for charging (e.g., using nanomaterial that has the ability to charge a battery by means of walking or solar energy). All the data can then be used to understand the user and provide valuable digital information. The data can also be used to keep track of the user's health (e.g., heart rate variability, temperature, oxygen, etc.).

## Are there any problems to consider?

With IoT, AR, wearables, and VR we can and are already collecting enormous amounts of data. We are in the "big data" era. As with most of the new technology, the intention is good, but everything has its "dark side." So far, the data that are being collected are mainly used for biased searches that are based on what you have searched for and clicked on before. With big data, governments and insurance companies can track you in detail and obtain very personal information about you (Russom, 2011; Raghupathi & Raghupathi, 2014) private things, such as what you have been looking at and how you move or walk. In the future, companies will probably not ask for your CV but for data about you, your eye and body movements. With such data, they will be able to know what you are interested in, how you seek and analyze information, how active you are, how much you exercise, how often you are sick, etc. I agree with Hong (2013) that the users who supply data to companies are the ones who should benefit, otherwise the system is likely to fail or be subverted. It is important to let the users be aware of what kind of data is collected and what it will and can be used for.

What about information overload? What will happen if all the IoT devices want to get your attention and start competing with each other to do so? They might start notifying you that you have not interacted with a given device for a long time. They may get points each time you interact with them, or you may get a discount if you have liked them, or have interacted more with one device than another. A light bulb in your home that has only 10 hours left before it stops working can suggest that you click now, because you can get 10 bulbs from Amazon at a really good price. All this might end up with tons of notifications directly in your face if it is not designed correctly.

There is a risk that we will get so used to HWDs that we will feel naked or helpless without them. These are similar to the feelings you get when you forget your smartphone at home, but these new feelings will be even stronger.

Nevertheless, I think and hope that IoT, AR, wearables, and VR can be used to help people to better understand each other, and to communicate with each other, and to understand and take care of our beautiful world.

# Conclusions

This thesis set out to develop and explore three tools that can be used for prototyping AR and IoT interaction and to introduce four interaction models for controlling IoT devices.

We found the three prototyping tools – WozARd, IVAR, and VRUbi – to be useful for prototyping AR and IoT interaction. WozARd is suitable for prototyping simple AR user interfaces with a mid-fidelity experience but does not support tracking (*Paper 1*). The two VR-based prototyping tools IVAR and VRUbi are suitable for simulations of more complex scenarios, since registration and tracking can be easily simulated. One important takeaway for organizations that develop IoT systems or services is to use VR to simulate different scenarios and interactions. VR-based prototyping can offer high fidelity experience at a relatively low cost (*Papers 2 and 3*).

The interaction models presented utilize two form factors – smartwatch and HWD – both of which did well during the experiments. They both focus on three aspects: discovering connected devices; selecting and controlling connected devices; and that the user not needing to start an application. An example of the later is that the user interface should just appear when a person enters a smart office. UbiCompass, which was developed for the watch form factor, has its strengths in discoverability and control of devices for simple interactions (*Paper 4*). In a similar manner, the three interaction models developed for the HWD form factor have their strengths in discovering and selecting IoT devices. With just a few devices to interact with in a setting, the three interaction models did not differ significantly. However, when the number of devices were scaled up, the World in Miniature model stood out as being especially demanding and time-consuming for the users (*Paper 5*).

# Further research

The emerging technologies of IoT, AR, wearables, and VR are evolving at a fast pace. As we can see in Figure 2, half of the products that we used in the course of this thesis research have become close to useless or obsolete. However, we have gained experience and learned from these “useless” products and the roles IoT, AR, wearables, and VR can play in the future. In this section, I will give an example of further research questions.

How can not-so-tech-savvy people set up and configure different IoT devices in a smart home environment? In this thesis I have focused on discoverability and interacting with IoT devices. However, in a real situation as a user you also need to set up and configure IoT devices. In my research, we used off-the-shelf products to develop and explore prototyping methods and interaction models. We found that each product manufacturer provides its own software, which often is an obstacle in combining technologies from different manufacturers. Open source projects work with middleware that supports all communication protocols such as ZigBee, Z-wave, and LoRa. Examples of such middleware projects are HomeAssistant, Homey and openHab. However, there is always a device from a specific brand that is not supported. Ideally, the not-so-tech-savvy person should not need to keep track of knowing if a certain product is ZigBee or Z-wave compatible; the person should just be able to buy any product and manage to set up and configure it without needing to install any application or follow a manual. At the application level, there is a similar attempt as with the middleware. It is an open source community called the Web of Things (WOT) founded late 2007 by two researchers, Guinard & Trifa (2007). Its goal is to build the IoT in an open, flexible, and scalable way, using the Web as its application layer. They work with three main topics: technologies; new ideas and new technologies; and end users and products. As they state, it is a very technical oriented community.

How can we utilize new VR technology for higher fidelity and a higher sense of presence? VR technology is currently entering a mature phase at the same time as a lot of new equipment is being developed that introduces other senses than sight (which received the most attention to date). Examples of other senses that are approaching the production line are 3D audio, olfactory feedback and haptic feedback. Adding more senses offers opportunities to study and analyze more complex and diverse situations, behaviors, social studies, security issues and privacy issues.

How do we collect cognitive attributes from AR or VR user studies? One way could be to exploit eye tracking functionality. For instance, Tobii has integrated their eye tracking technology into the HTC Vive. The eye movement data could then be used to produce scan paths and heat maps in order to understand how the participants guide their visual attention. Another way is to adopt standard questionnaires and develop a VR version of them so the user does not need to take off the HWD after each task. In addition, the interviews should perhaps be done in the VR world. Another idea could be to make use of the movement data generated by the tracking system that controls the virtual representation of the user's own body. This data could be matched with anthropometric databases in order to perform basic ergonomic analyses of gestures that are part of an AR interaction concept.

# Relevance to society

IoT, AR, wearables and VR are the emerging technologies that will become an increasingly important part of modern society. Traditionally, both AR and VR applications have emerged in the gaming area. However, since the relatively low cost of hardware and all the functions the modern game engine offers, this opens up a much broader spectrum of areas where both AR and VR can be applied. I will briefly give examples of how the emerging technology is relevant to society and of how the prototyping methods are relevant to industry, and how the proposed interaction models are relevant for society.

The emerging technologies are relevant to society in many areas including, sustainability, digitalization, education, and health. IoT will play the role of connecting things via the cloud and collecting data from almost everything. AR will play the role of being the user interface. The role of wearables will be the bridge between the physical and digital, presenting things for the user but also sensing the user and the environment. The VR role is to increase knowledge of things, humans, cities, countries, the world, and the universe. Almost everything can be optimized to be used only when absolutely needed. For example, at home, energy usage can be reduced by only turning on the lights and heat when needed. The same example can be applied to cities and countries. We can share things between neighbors; wearables can sense and track our health and ultimately extend and even save our lives.

How is my research relevant to industry? Prototyping IoT interaction with the current methods and tools is complex and expensive. The methods and tools roughly include paper prototyping or software development. This leaves a gap between interaction designers and developers when it comes to exchanging complex ideas. They never get the chance to visualize their thoughts and test their designs at an early stage. VR-based prototyping allows organizations working with IoT to be more innovative and cost efficient in trying out new designs, interactions and product ideas.

The interaction models presented were designed for both the home environment and the office environment. The same principles of the proposed interaction models can also be applied in other environments in society as well. For instance, if someone visits a new location – an office or a public place – the idea is that the visitor is automatically provided with relevant information. The things the person is allowed to control would be presented through a smartwatch as proposed in Paper 4 or through an HWD as proposed in Paper 5. The WIM interaction model could be used to quickly get an overview of the building and determine if all the lights are turned off and all the doors are locked.

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