FAKULTÄT FÜR !NFORMATIK
Faculty of Informatics

Take Me Home

Designing, Implementing and Evaluating Wayfinding Prototypes for People with Dementia

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Markus Wojtak

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Kurzfassung

Mit steigender Lebenserwartung steigt auch die Anzahl von Menschen, die kognitive Schwächen aufweisen. Obwohl es diverse technologische Mittel gibt, die ihnen im Alltag zuhause (z.B. Assisted Ambient Living) oder in Altersheimen helfen, wird dieser Bereich außerhalb dieser kontrollierten Umgebungen meist vernachlässigt. Dabei hat Forschung auf diesem Gebiet gezeigt, dass körperliche Aktivität hilfreich bei der Verlangsamung der Ausbreitung von Symptomen, wie Gedächtnisschwund, ist. Jedoch ist das Risiko, zu vergessen wo sie wohnen, für Menschen mit Demenz groß. Da die meisten Menschen inzwischen Smartphones, die Standardortdienste mittels globaler Navigationssysteme bereitstellen, benutzen oder zumindest mit sich tragen, erscheint es sinnvoll, diese Technologie einzusetzen, um dem entgegenzuwirken. Während Karten- und Navigationsapps, wie z.B. Google Maps häufig in Verwendung sind und Menschen dabei helfen, an einen bestimmten Ort zu finden, erscheinen diese Apps Menschen mit kognitiven Schwächen unter Umständen zu kompliziert, da eine größere Menge an Funktionen und Optionen enthalten ist. Diese Diplomarbeit beschäftigt sich mit der Erforschung einer neuen Art, Menschen nachhause zu leiten, indem zwei Prototypen entworfen, implementiert und evaluiert werden. Als Inspiration für die Prototypen fungierte ein analoger Kompass, oder genauer gesagt die Analogie einer Nadel, die in Richtung eines festgelegten Ziels (Norden) zeigt. Anders als bei einem herkömmlichen Kompass, zeigen die Prototypen dabei allerdings nach Hause. Die Diplomarbeit bietet zuerst eine kurze Zusammenfassung der Demenzthematik bevor ein Überblick über die Technologie hinter globalen Navigationssystemen gegeben wird, bevor der kreative Prozess, der zu den endgültigen Versionen der Prototypen geführt hat, genauer betrachtet wird. Da die Zielgruppe für die Prototypen Menschen mit kognitiven Schwächen miteinbezieht, mussten zuerst Anforderungen für die Prototypen festgelegt werden, die die besonderen Bedürfnisse dieser Gruppe berücksichtigen, bevor mit dem Designprozess begonnen werden konnte. Hierzu wurde Literatur zu diesem spezifischen Thema herangezogen. Der erste Prototyp, der in dieser Diplomarbeit vorgestellt wird, ist eine iOS App, der zweite Prototyp ist ein Gerät, welches die App im Hintergrund verwendet. Die informelle Evaluation deutet an, dass das in dieser Arbeit entwickelte Konzept positiv aufgenommen wird und das Potential hat, Menschen erfolgreich nach Hause zu leiten.

Abstract

With increasing life expectancy, the number of people with cognitive disabilities like dementia is increasing. While technological aids exist to aid them at home (e.g. assisted ambient living) or at nursing homes, research has shown that physical activity is beneficial to slowing the progress of memory decline. When leaving their home, people with dementia are at risk to forget where they live and therefore become lost. As most people use or at least carry smartphones that utilize global navigation satellite systems (GNSS) for location services, it seems logical to leverage the technology. While mapping and navigation apps such as Google Maps are helpful for a majority of people in this context, people with cognitive limitations may find them too hard to use as the respective user interface contains a large amount of elements and possible options. This thesis explores a new way of guiding individuals home by designing, implementing and evaluating two prototypes. The prototypes were initially inspired by an analog compass, or more specifically, the analogy of a needle pointing towards a predefined destination (i.e. north). However, unlike a traditional compass, the prototypes developed point towards the homes of users. The thesis first provides a brief summary on dementia before moving on to an overview of the technology behind global navigation satellite systems. The ideation process for both prototypes is covered in detail while providing an overview of the design process that led to the final versions of the prototypes. As the focus group includes people with cognitive limitations, requirements for the prototypes taking the needs of this specific group into account had to be determined first by forms of a literature study before starting with the design process. The first prototype developed is an iOS app while the second prototype is a physical device that is meant to be used in conjunction with the app. The informal evaluation suggests that the concept developed over the course of this thesis has the potential of successfully guiding individuals home as it has been positively received.

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CHAPTER 1

Motivation and Context

This chapter serves as an entry point to the thesis. First, a summary of the motivation that led to this thesis will be given in section 1.1 before moving on to an explanation of dementia in section 1.2 and introducing the Way-Key project in section 1.3. The chapter concludes with a brief overview of related work in section 1.4.

1.1 Motivation

With increasing life expectancy, the number of people being diagnosed with memory decline, such as dementia, is rising. For these people even simple tasks, such as for example finding their way back home, may become challenges. Disorientation can also cause greater problems: being lost may lead to constant anxiety of getting lost and as a consequence to withdrawal from participation in social life.

However, getting lost is not only occurring to people with memory decline. In the last ten years, smartphones have become a part of our lives. With the widespread adoption and the possibility of running different sorts of applications, map apps (e.g. Google Maps) have become commonly available and are being frequently used for navigation. While a majority of users may find these apps intuitive and easy to use, people with cognitive limitations may be overwhelmed by the user interface and the amount of information provided as navigational functions represent only a small subset of all available functions in map applications.

The aim of this thesis is to design and develop multiple prototypes that help elderly people and those with dementia with the task of finding their way back home on their own. Whether a concept is feasible will be explored by evaluating it in a real world context. It is expected that multiple iterations will be necessary to design prototypes that are of practical use to the target group. The main challenge will be to design simple, yet accurate and usable interfaces while paying attention to the specific needs of elderly people.

1.2 Dementia

Due to longer life expectancy as a consequence of technological advancements leading to better disease prevention and treatment, the world population is aging. As a consequence of living longer, cognitive disabilities including dementia and Alzheimer's disease are being diagnosed more often. Dementia is a syndrome in which there is a deterioration in cognitive function[1]. While various types of dementia exist, Alzheimer's Disease is the most common one with 60 to 70 percent of all dementia cases[2]. With Alzheimer's, getting lost in familiar places mostly occurs at the middle stage in contrast to dementia in general, where this occurs at the early stage. Dementia can be categorized into three stages which represent the severity of the condition.

Because of the rising number of the diagnosed cases of dementia, it is important to look at the factors that influence the risk of developing dementia. In 2015, dementia affected close to 50 million people worldwide. By 2050 the number is expected to triple[3]. With rising numbers comes increased cost for public health care systems. Therefore, there is a large amount of research directed at preventing the occurrence of dementia. Out of the identified factors increasing risk of developing dementia, one of the main factors is considered to be lack of movement[4]. As physical health has a positive effect on cognitive functions[5], it is important to develop new or augment existing technologies that enable elderly people to still move freely while reducing risks (e.g. getting lost) even though physical activities typically decline with increased age[6]. Independence can also be considered as playing a key part in inclusion and engagement in society[7]. To promote independence, future technological aids should be designed in a way that allows for easy integration into the daily routines of people with dementia[8].

Although physical activities (e.g. going for a walk) have a positive effect on cognitive functions, advances in indoor environments (e.g. smart homes, ambient assisted living) helping individuals exhibiting cognitive limitations with coping with their disabilty[9], have in general not yet led to similar advances in outdoor environments[10]. Although many technological aids for dementia exist, most of them do not consider people with dementia actively, leading to design decisions that can in turn lead to people ultimately mistrusting some of these aids. As a study has shown, surveillance can be considered freeing in the context of not requiring living in nursing homes but at the same time privacy concerns have to be considered[11]. While technologies that make use of some form of surveillance are developed constantly, not all stakeholders value related aspects accordingly as shown in a study[12] although considering all involved groups of people equally should be a key requirement.

For dementia, the early stage is characterized by (amongst others) forgetfulness, losing track of time and becoming lost in familiar places. Forgetfulness and the loss of orientation lead to individuals with dementia experiencing higher risks of getting lost[13]. Such situations can lead to life-threatening circumstances[14]. However, as a study has shown, tracking technology can be considered helpful for people with early stage dementia[15]. Even before smartphones have become common, research indicated that smartphones could be helpful in a care context[16]. Although some solutions exist, usage of GPS systems in dementia care is still low[17].

Most existing solutions include tracking devices that are supposed to help care personnel with locating dementia patients that have gotten lost or are exhibiting wandering behavior. Human computer interaction (HCI) research should focus on all involved stakeholders and value their needs accordingly. One of the projects directed at allowing people with dementia to make their own decisions while stile allowing for a safety net for caretakers and respecting the privacy of individuals affected is the Way-Key project which will be the focus of the next section.

1.3 Way-Key Project

Way-Key is a project funded by the FFG (Austrian Research Promotion Agency) that aims to develop technological artefacts to assist dementia patients with navigation[18]. Over the course of the project, three prototypes have been designed. The first was a cooperative day planner that allowed people with dementia to structure and communicate their schedule. Reflecting on their upcoming plans could activate the memory of individuals and lead to emotional connections with some to-dos and increase commitment for various daily activities.

The second was a context aware guide with the purpose of providing individuals in a state of momentary disorientation with help. The idea was to use an emergency button which, after invoking it, would allow relatives or caretakers (taken from a predefined list) to reach the person via phone, calm them down and provide them with directions in order to guide them to a place they know or to reassure them and come to pick them up.

The third prototype was a smart geofencing app that in contrast to normal geofencing applications would analyze movement data based on the habits of the individual using it and draw deductions whether locations lie within safe areas. The prototype only simulated this behavior. The idea behind the prototype was that most individuals own a smartphone but mainly use them for calling, thus not utilizing any advanced functions. As smartphones in general have a GNSS-capable chip, they can be used for tracking purposes. If the prototype would classify the location of an individual as unusual, (e.g. indicating wandering behavior), relatives could reach the person with dementia and ask whether any help is needed.

With all three prototypes, privacy related issues have been taken into consideration to avoid designing technology that is degrading its users based on their cognitive limitations[19].

1.4 Related Work

Several prototypes for people with cognitive limitations have already been developed. One such example is the NavMem Explorer that uses turn by turn navigation augmented with photos of landmarks that have been added by the user. The design features three aspects: Separation of a complex task into less complex tasks, relying on the existing knowledge of users and making use of photographs taken by the user when possible. The app provides users with two views for the wayfinding process: while a map view can be used for orientation purposes, an arrow pointing to the next waypoint, as well as a list of the next landmarks is used for navigational purposes[20]. Another approach is aimed at being as simple as possible: "Home Compass" features an arrow and distance information that entices users to explore their neighborhood while still keeping a reference to their home. Additionally, the app uses vibration feedback that enables users to utilize the app without having to constantly look at the smartphone[21].

The development of these technological aids can prove to be a challenge, as techniques used for usability evaluations, such as thinking-aloud may not be feasible due to people with dementia having difficulties in verbalizing or narrating current tasks. As their short term memory may also be affected, possible issues that arose during the use of the technology may not be remembered[22]. A way to overcome these difficulties is presented in [23]: caregivers can log emotions of people with dementia using the prototype "Proxemo", a smartwatch app that features Emojis that represent how a person using the technological aid that is being evaluated currently feels. In combination with a synchronized video recording, valuable insight can be gained.

Besides challenges with testing new technologies, there is also one major problem with healthcare technologies that were designed for use by people with dementia: people using it may be seen as deficient and thus the technology is only being used to fill gaps left by impairment[24]. A possibile solution for this is described by Ng et al. in [25]: usage of artificial intelligence is suggested to provide a safety net for people with dementia that exhibit wandering. In contrast to most existing tracking systems that are designed in ways that demote people with dementia to objects that are being tracked, the suggested approach aims at helping users to find their way on their own while still providing caretakers with an option to intervene if necessary. The thought behind this is quite important: people with dementia must not feel like they are being constantly monitored and observed. As another study points out, implicit assistance for people with dementia can be very effective. Navigational cues like lights can be used to guide people indoors without explicitly providing directions[26].

This chapter included details on motivation and context of this thesis. The focus of the next chapter will be the technology allowing to receive location data.

CHAPTER 2

Guiding by Global Navigation Satellite Systems

This chapter will focus on the technology that is used behind the scenes by tracking devices and by the prototypes covered in this thesis. First an overview of the history of global navigation satellite systems will be given in section 2.1 before outlining the current state of technology in section 2.2 and giving a brief summary of problems relevant to the prototypes developed in this thesis in section 2.3.

2.1 History Overview

Global Navigation Satellite Systems (GNSS) ensure the availability of global real time location data. While at the time of writing there are a few different systems in use, the Global Positioning System (GPS), built and operated by the United States of America was the first. The first satellite launched in 1978 and the system became fully operational by 1995. Until May 2000, GPS provided accurate position information only to authorized users to prevent potential enemies of the United States from gaining exact location data. Signals were artificially degraded for non authorized users, leading to a horizontal accuracy of approximately 100 meters. After *selective availability*, as it was called, has been turned off, GPS could be used for general purposes by individuals around the world. This lead to the widespread use of GPS technology in car navigation systems.

Russia's Global Navigation Satellite System (GLONASS, transliteration Globalnaya navigatsionnaya sputnikovaya sistema) shares some similarities with GPS and its signals can be used in conjunction with GPS signals to achieve a higher accuracy. As is the case with GPS, it was intended for use by both military and individuals and high accuracy location data was initially not available to civilians. Since May 2007, individuals have access to accurate position information[27].

Currently, GPS and GLONASS are the only systems that have world wide coverage. Additional regional systems that are scheduled to provide world wide coverage include China's BeiDou and the European Union's Galileo. Unlike GPS and GLONASS, the European Union's Galileo is not operated by a military force and it was initially designed for civil use only. It became operational in December 2016[28] and features an accuracy of a few meters for unencrypted civil signals[29].

In 2008, Apple introduced a location based API (application programming interface), CoreLocation, which could be used to create different sorts of applications that utilized location data. This was an important step for location based services as back then, individuals used GPS mainly in car navigation contexts. In addition, these navigational tasks were not fulfilled by smartphones but by special navigational systems which were only used for this single purpose. Soon after, Google's Android system was released also allowing to use location data for other purposes than vehicular navigation leading to widespread availability of location services in common devices.

2.2 State of Technology

As explained earlier, to provide individuals with accurate location data, various global navigation satellite systems are used. Each of these systems can operate on its own and consists of an array of multiple satellites orbiting the earth. As of March 14, 2018, the GPS constellation consists of 31 operational satellites[30]. The satellites orbit the earth in a way that allows to have at least four of them in direct view from almost any location on Earth. When there is a sufficient number of satellites in view, trilateration or multilateration can be performed to determine locations. The minimum number of satellites required is four as there are four unknown variables (X, Y, Z and time). For determining location data, precise time data is required as the satellites transfer time data that is used by receivers to estimate the distance on the basis of the speed of light. In addition, as all GNSS feature only one way connections (i.e. broadcasts), all required information must be transmitted and interpreted without relying on queries.

While location services are being commonly referred to as *GPS*, most receivers have the technical capability to use multiple satellite systems. Newer smartphones in general are able to leverage the data of multiple satellite systems for improved accuracy. Apple's iPhone 8, 8+ and X were initially the only iPhones able to receive positioning data provided by Galileo. At the time of writing, the iPhone 6s, 6s+, 7 and 7+ are also listed as being Galileo compatible though.

While there are many different techniques that allow to calculate more precise location data, smartphones in general do not make use of them. To allow for faster GNSS signal acquisition though, smartphones often use assisted GPS (A-GPS). With A-GPS, a broad estimate of the device's position is obtained to make calculations of the location much faster as standalone GPS takes approximately 40 seconds until an initial position fix can be achieved. The prototypes developed in this thesis and covered in detail in the next two chapters rely on the CoreLocation API mentioned earlier to get location data.

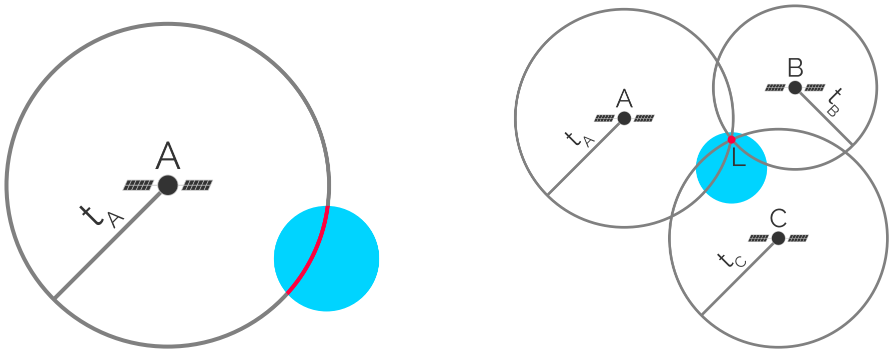
While CoreLocation does not grant access to specific parameters (e.g. the number of satellites, signal strength) it provides location data within a matter of seconds due to the use of A-GPS and location data that was obtained by previously analyzing WiFi networks within range.

Smartphones in general can determine a location with a radius of uncertainty of approximately five meters in best case scenarios. In cities, direct line of sight to satellites is often blocked by buildings, resulting in a larger radius of uncertainty. Another factor that influences the position accuracy is how far apart satellites are spread. If they are spread wide apart, the signal will in general be more reliable compared to a narrow spread.

The basic working principle of GNSS position determination can be seen in figure 2.1. To simplify the illustrations, only a 2D coordinate system has been used and perfect clock synchronization is assumed. In reality, spheres in a 3D coordinate system are used instead of circles. For the illustration, A, B and C symbolize satellites, t_A, t_B, t_C symbolize the time it took to receive a signal. As satellites transmit time signals, the difference between the receiver time and the received satellite time allows for distance calculations. As seen in figure 2.1a, if signals from only one satellite are received, no accurate position can be calculated. It can only be determined that the actual position is located somewhere on the perimeter of the circle that was created using the time difference. However, as it can be assumed that the position is on planet Earth (blue circle), only a small portion of the perimeter has to be considered, effectively narrowing down the range of options. As the range still covers a vast area, no location can be inferred. If signals from at least three satellites are received, the actual position (red dot, labeled L) can be determined by calculating the intersection of all circles as seen in figure 2.1b. As in the case of only one satellite, the position could in theory be determined by intersecting two circles, as the location can be considered to be on this planet. However, three satellites only allow for determination of 2D positions. In addition, the determined position will only be correct under the assumption of being at sea level. To calculate a 3D position, signals from at least four satellites are required as there are four unknowns as mentioned earlier.

In reality, receiver clocks will in general never be as accurate as satellite clocks, which use atomic clocks[31]. Therefore, it is likely that there will be multiple intersection points (depicted in yellow) and not just one precise intersection point as seen in figure 2.2. To correct for clock synchronization issues, receivers correct their clock by comparing it to the received time signals. After the local clock has been corrected, determining a precise position (red dot, labeled L) is possible.

As the examples provided earlier assumed perfect visibility of satellites, an overview of issues that are relevant in the context of this thesis and have an impact on the quality of received signals will be provided in the next section.



(a) One satellite (b) Three satellites

Figure 2.1: Illustration of the basic working principle of GNSS position determination assuming perfect clock synchronization in a 2D coordinate system

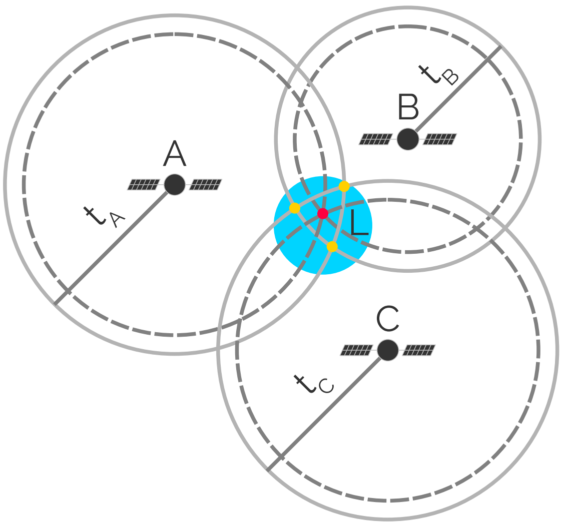


Figure 2.2: Illustration of clock synchronization for GNSS applications to determine an accurate position in a 2D coordinate system

2.3 Issues

One of the most common problems occurs when signals are blocked by walls, buildings or roofs as pictured in figure 2.3. However, after the launch of the Galileo GNSS, tests performed indicate that using Galileo in addition to GPS and/or GLONASS significantly improved accuracy in urban canyons and indoors[32] therefore reducing the likelihood of completely blocked signals.

When moving through urban canyons, GNSS receivers that do not make use of A-GPS can have a hard time acquiring an initial fix. This is due to the fact that to determine a satellites position, its complete ephemeris data is required. If the signal from a satellite is lost while receiving ephemeris data, the data is discarded and receivers have to collect the data from scratch. As each satellite has its own ephemeris, this process has to be repeated separately for every satellite the receiver is receiving signals from. To assist receivers, each satellite broadcasts almanac data containing information about other satellites.

The accuracy of acquired positions depends on multiple factors. First, the number of satellites signals are received from is the most important factor. The second factor is whether signals are received directly. When signals bounce off buildings or other objects before reaching the receiver (multipath) as illustrated in red in figure 2.4, the reported location can deviate from the actual location. While there are techniques to determine whether signals have bounced off surfaces in order to reject them, the first factor comes into play: without a sufficient number of satellites in view, the multipath signals can not be identified and rejected thus leading to positional deviations.

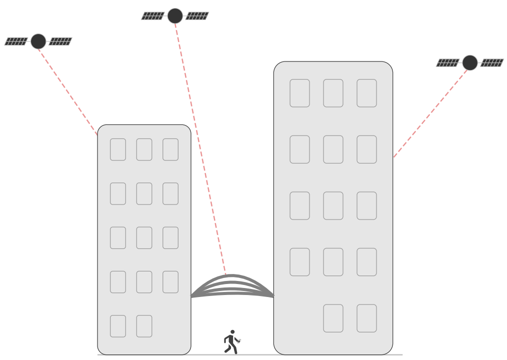


Figure 2.3: Illustration of blocked GNSS signals in an urban canyon

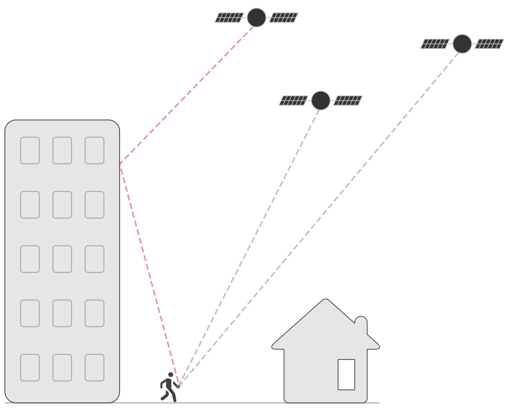


Figure 2.4: Illustration of the GNSS multipath problem

While the mentioned problems can have an impact on the prototypes discussed in the next two chapters, efforts have been made to keep possible side effects to a minimum. The software prototype, the Take Me Home app, will be the focus of the next chapter.

CHAPTER 3

Software Prototype

This chapter will focus on the software prototype that was developed as part of the thesis. First, an explanation of the inspirations that influenced the initial design choices is given in section 3.1. Next, the requirements for the prototype and the choices concerning the interaction design will be covered in section 3.2. Details concerning the implementation, including used technologies, hard- and software are featured in section 3.3. The following three sections cover the design of the compass (section 3.4), the app (section 3.5) and the setup process (section 3.6).

During development a set of limitations was discovered that will be the focus of section 3.7. Most of these limitations were determined with the help of the logging function that is built into the app which will be described in section 3.8. Apart from technical limitations, there was also a human component that led to additional limitations as outlined in section 3.9.

The chapter will conclude with section 3.10, containing information about the evaluation of the prototype.

3.1 Inspiration

The basic inspiration for the prototype was an analog compass. While usage of a compass for pedestrian navigation may not be intuitive by itself, the analogy of an arrow pointing towards a set destination (i.e. north for a classic compass) should be self explanatory and thus appear simple enough to be understood intuitively without requiring textual descriptions. Another benefit of the compass metaphor is that no interaction with the compass is required as it points north by default. Building on this inspiration, requirements have been determined that influenced both graphical and interaction design and they will be covered in the next section.

3.2 Requirements and Interaction Design

To create a user interface (UI) that takes care of the changed needs of people with cognitive disabilities [33], certain factors have to be considered.

As people with dementia may get overwhelmed when provided with too many options to choose from, the user interface should be as basic and simplistic as possible[34] while still providing enough information for individuals to reach their destination (i.e. find home). Therefore, the single most important requirement is that the user interface must appear simple and in no case look cluttered to avoid an unsuitable mobile design that could lead to the rejection of the app by older people[35]. Consequently, no distractions should be placed on the screen, instead focusing on only including content that is required and beneficial for solving the navigational task at hand. In addition, the user interface should be self explanatory and thus contain no text as people with dementia may not be able to comprehend its meaning while being in a state of feeling lost[1]. The app must use colors that provide enough contrast to the background in order to ensure good visibility independent of the lighting conditions (e.g. the UI must be visible in direct sunlight)[36].

To minimize cognitive load, the prototype should be designed to function without any user interaction at all (once the initial set up, covered in section 3.6, is complete). As a consequence, the app should be perceived as easy and intuitive to use as personal beliefs can greatly influence how successful a new technological tool may appear[37].

As a study by Montuwy et al. has shown, visual feedback for navigation purposes is perceptible while not being overly disorienting[38]. Constant haptic feedback may not be considered pleasant, therefore haptic feedback should be employed infrequently and only when there is a clear benefit. The app must not rely on haptic feedback as any form of vibration can be turned off in the system preferences without apps being notified about it.

The next section will cover details of the implementation and describe the technologies and devices that have been used.

3.3 Implementation

The prototype has been developed for Apple's iOS 11. It was built using Xcode 9 and programmed in Swift 4.1. Tests were performed on various iPhone models to cover all available screen sizes and display technologies as well as to account for differences in processing speed to ensure the prototype works on all devices that are able to run iOS 11. While the app does also work on iPads, it was decided to focus on iPhones.

The prototype has been tested on:

- iPhone 5S, iPhone SE: 4" LCD display
- iPhone 6, iPhone 6s: 4.7" LCD display

- iPhone 6s+: 5.5" LCD display
- iPhone X: 5.8" OLED display

In order to allow participants of the test phase to run the app on their own devices, Apple's Testflight platform was used as it allows for apps to be beta tested before releasing them to the App Store.

During the requirements assessment, it instantly became apparent that guiding people home had to be achieved by taking map data (i.e. data that includes streets and sidewalks) into account instead of simply pointing them in the direction their home is located at. Apple Maps is being used as a routing information provider. Due to the fact that Google does not permit usage of its directions API when the returned route is not placed as an overlay on a Google map[1], using Apple's map service for directions proved to be a suitable alternative.

The general operating mode of the app can be described as:

1. Determine the user location with the inbuilt GNSS receiver
2. Request walking directions to the destination from the Apple Maps directions service
3. Create a polyline (continuous line composed of multiple line segments) from the returned route
4. Guide users to the next polyline segment until they reach the destination

To guide people along the route, the internal compass is used. The app does take the magnetic declination into account (e.g. 4.3° for Vienna at the time of writing) and thus uses geographic north instead of magnetic north. Points on the polyline are divided in waypoints and turning points. A turning point is a waypoint that had directions associated with it when it was returned by the directions API. While the app features no textual representation of these directions, haptic feedback is used to inform users of an upcoming turning point. In this way, the app can theoretically be used without having to look at the screen constantly as it can be assumed that the compass will point forward while walking along a street that is represented by polyline segments. To avoid possible confusion, no vibration patterns (e.g. vibrating once for a left turn and twice for a right turn) are used. Instead, vibrations are meant to inform users of an event that requires their attention and therefore have individuals look at the screen to determine what to do.

When the device used is located closer than 25 meters to the destination, the app displays the selected destination address along with an icon representing a house to convey the meaning of *home* without using a specific written language. Because of GNSS inaccuracies,

[1] https://developers.google.com/maps/documentation/directions/policies

this approach appeared to be a fair compromise between the goal of not using text in the app at all and featuring accurate directions. As it is more likely for individuals to recognize areas close to their home, this compromise allows for encouraging individuals that they are already in a close vicinity to their home while at the same time allowing other people to help someone who is lost by utilizing the shown address. As the radius to the destination should be less than 25 meters, it is likely that someone in the vicinity can provide assistance to the person that is lost or at least help them find their home.

In the next three sections, the main user interface components will be covered. The most important component of the app (the compass) will be presented first, followed by another section containing the other factors that influenced the app design. The third section will provide insights on the setup process.

3.4 Compass Design

As mentioned in section 3.1, the inspiration for the prototype was an analog compass utilizing a needle pointing towards north. The very first design idea for the compass component mimicked an analog compass, or more specifically, the shape of a needle that points towards the next waypoint and is shown in figure 3.1. During the first test it immediately proved not to be suited for the app because of the erratic behavior that resulted from hand movements and slight direction changes while walking. The fact that route points are located in the middle of streets and not on sidewalks, as will be explained in section 3.7, led to another problem: the compass never pointed straight ahead when walking towards a route point (i.e. end of a polyline segment). When the route point was located far (e.g. 100 meters) away, the needle seemed to point straight ahead. However, the deviation continuously increased while getting closer to the route point. As this behavior could not be considered intuitive nor acceptable, a new concept for the compass was required that took these limitations into account. Ironically, the final issue was the resemblance to a compass, which could be considered to be a precise instrument by individuals. The accuracy of the prototype on the other hand depends on many factors and will, in general, never be able to match the level of precision a compass can provide, possibly leading to false expectations.

The second design idea exchanged the arrow for an arc to compensate for inaccuracies. Additionally, a circular sector, representing the user's field of view, was added. When discussing this idea with other people, it was decided that the arc will rotate instead of the circular sector. As a result, the circular sector provides a reference for the user as it remains static and indicates the direction the top of the device should point to. In addition, colors will be used to differentiate between correct and wrong directions. To avoid changing colors constantly and to provide users with positive feedback when pointing the device in the correct direction, ranges will be used instead of absolute directions.

One of the personal goals when designing the prototypes was to feature a modern design that could make the app look appealing to individuals of any age. This approach should

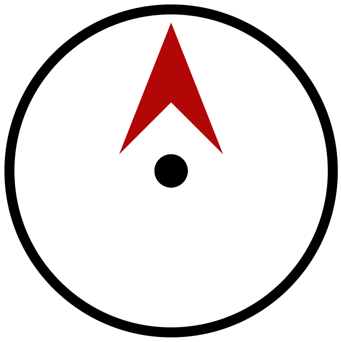
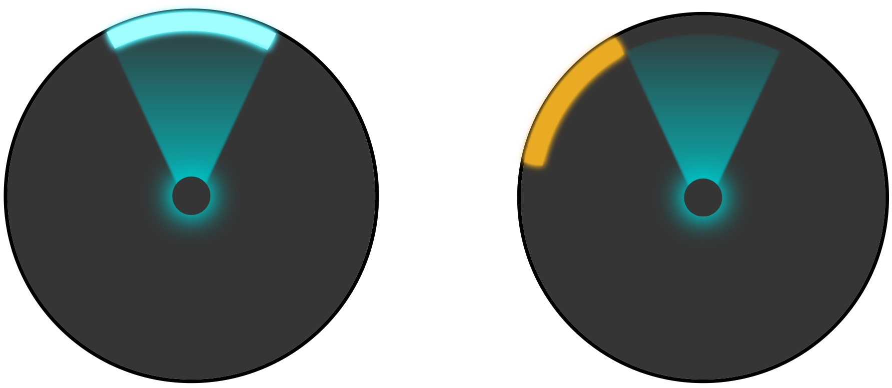


Figure 3.1: Illustration showing the first compass design concept for the prototype, featuring an arrow

also prevent the occurrence of a stereotype threat[39]. Stereotype threat is the fear of failing because of stereotypes about the group the individual belongs to[40]. For example, younger individuals could disapprove of using the app if it looks like it is made for people with cognitive disabilities or for elderly people only.

Therefore, the new concept introduced a modern design to avoid creating an app that would look plain and old fashioned while still maintaining good visibility in various lighting conditions. The color scheme applied to the arc that was used to differentiate between right and wrong was light blue when pointing the device in the correct direction and orange when pointing the device in any other direction. The concept can be seen in figure 3.2. While this concept worked much better than the first one, some improvements were necessary before trying the concept on a device. Because the arc featured the same length as the width of the circular sector, there was room for confusion whether the arc had to match the cone perfectly.

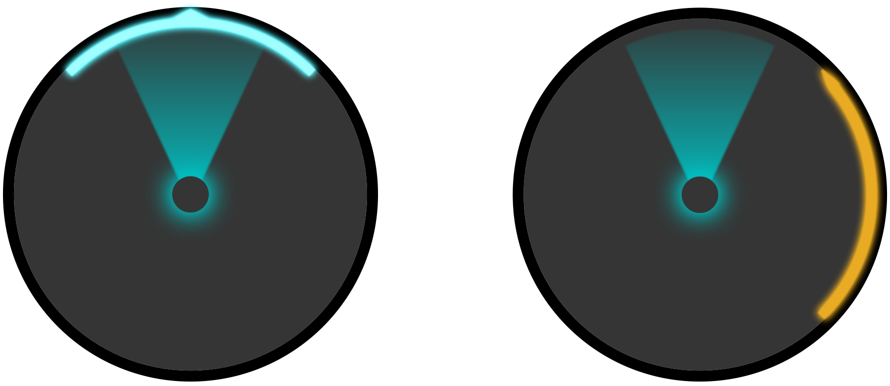


(a) Device pointing in the correct direction (b) Device pointing in the wrong direction

Figure 3.2: Illustration of the second compass concept for the prototype, featuring an arc instead of an arrow

Building on the previous concept, the next iteration featured some changes and can be seen in figure 3.3. The arc length has been increased to better represent the inaccuracy of the prototype. The term *correct direction* will be used as *pointing in the correct absolute direction in degrees ± half of the arc length* from this point on. One of the difficulties with the previous design concepts was the inability to test how they will perform when in actual use. The third prototype was the first one that was implemented and then tested by individuals that had no knowledge of the concept. Feedback from these individuals indicated that the design performed favorably although the arrow in the off track state led to some confusion.

As pictured in figure 3.3b, when the arc was rotated to the right, the triangle pointed to the left but the device had to be rotated to the right to get the arc above the circular segment. In an attempt to improve this function and make the compass more intuitive, the triangle was tentatively placed on the opposite side of the arc. Unfortunately, there was no improvement. As feedback from another person brought up the fact that the triangle was very hard to see, this part of the concept had to be discarded and a different approach was required.



(a) Device pointing in the correct direction (b) Device pointing in the wrong direction

Figure 3.3: Illustration of the third compass concept for the prototype, featuring longer arcs and arrows

The final design iteration is pictured in figure 3.4. As in the previous iteration, the arc features a triangle in the center. The shape of the arc and the triangle remain consistent independent of the orientation. This approach leads to a more streamlined design and prevents animation issues. When pointed in the wrong direction, two arrows are shown that indicate the direction in which the user should rotate the device. To further emphasize the meaning of the arrows and the circular segment, a glyph representing a person's head is always displayed in the center of the compass. To add implicit meaning to the two states the compass can be in, a new color scheme has been introduced. Green now represents pointing in the correct direction and orange represents pointing in the wrong direction. While developing this concept, a reddish color was considered but quickly discarded as red color tones may be interpreted as being overly negative. The idea behind using a shade of orange is to feature the color as attention grabbing but not necessarily as wrong as the app will inevitably change to this state sometimes even when heading in the correct direction.

To prevent showing the color orange and thus providing potentially negative feedback too often, a third state was introduced (see figure 3.4b) as an extension. When the device orientation is off by more than ± half of the arc length from the center, the color of the compass will change to yellow. The state is internally defined as *undefined* as it implies that the user may be off course but it can not be determined with enough confidence. The arrows indicating that turning right or left is required are not shown in this state. When the orientation is off by more than the full arc length, the user is likely off course, therefore the state pictured in 3.4c (orange color scheme) is applied.

The compass component (excluding the person icon) is rendered on device. As a consequence, various parameters of the concept can be changed directly in the code leading to the possibility of applying changes dynamically. For example, the arc length and the circular segment width can be adjusted. All parts of the compass are being colored on screen allowing for a change of the used color scheme. The idea behind this approach was to allow individuals to choose their favorite color instead of green to make use of emotional connections and associations that individuals may have. Ultimately, the function of selecting a favorite color has not been implemented, as it can be considered doubtful whether short time evaluations would take this feature into account and allow for individuals to reflect on its usefulness.

(a) Correct direction (b) Possibly wrong direction (c) Likely wrong direction

Figure 3.4: Illustration depicting the final compass concept for the software prototype, featuring improved arrows and improved colors

The developed prototype consists of more than just the compass component. Additional user interface elements and other factors that influenced the app design will be covered in the following sections.

3.5 App Design

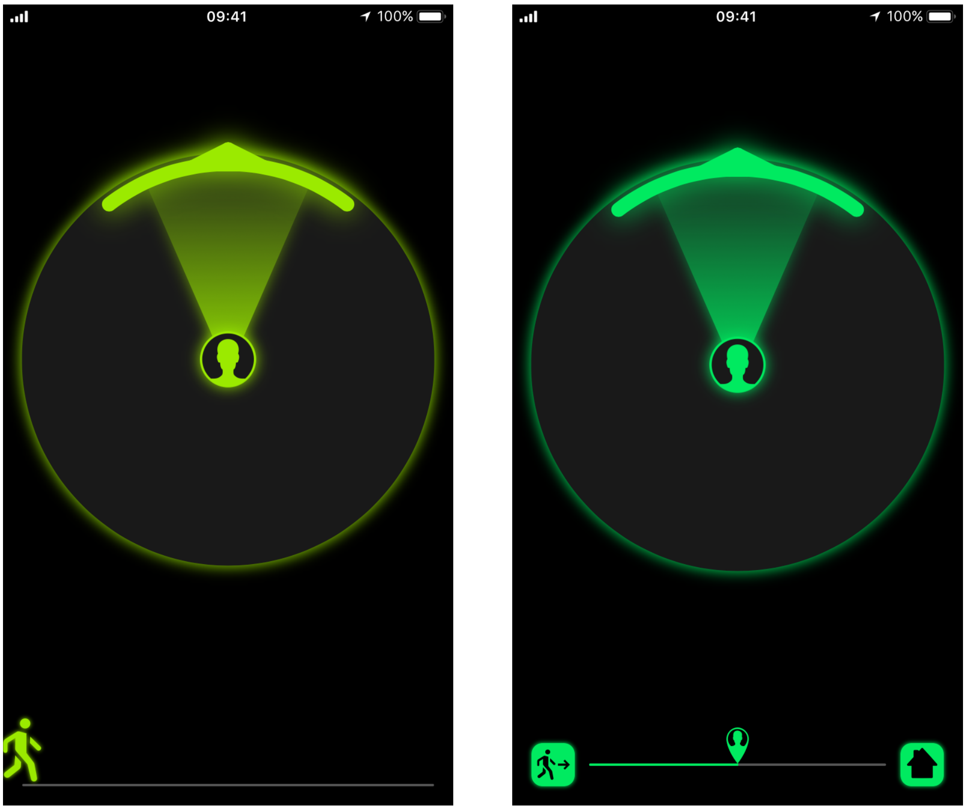
While the most important part of the app is the compass component covered in the previous section, additional user interface elements became necessary even though the app was initially conceptualized as having as little elements visible on the screen as possible in order to avoid distractions. Guiding people towards their home seemed to be functional with the compass part of the app alone. However during one of the first evaluations the lack of any indicator whether the app was actually pointing in the correct direction raised valid concerns.

To provide a form of discernible feedback, a progress bar has been implemented. The design concept included only a plain progress bar at first. However, during the very first evaluation of the progress bar, it became apparent instantly that it lacked any indication of its meaning. The major problem was the state of the bar at the beginning: it was empty and thus only a single-colored (gray) line was displayed. In an attempt to add meaning to the bar, an icon featuring a walking person was used that moved along with the progress on the bar. It can be seen in figure 3.5a. While this concept definitely showed some improvement compared to a plain progress bar, the issue with the state of the bar at the beginning was still present. Tests confirmed that the meaning of the revised bar was still not clear. In addition, the user interface did appear unbalanced whenever the icon was not positioned in the middle of the screen.

The design was improved with two icons representing the start and end points that have been added at the respective sides. The icon previously representing a walking person has been replaced with an icon that features a human head (as in the compass) with a triangle-like bottom part that provides feedback on the relative position of the user. It is believed that this approach should mostly eliminate the need of textual descriptions as the combined progress bar component should provide enough clues for individuals to instinctively understand its function. It can be seen in figure 3.5b.

To further improve the progress bar, additional modifications have been made. As explained in section 3.3, the app uses a polyline for guiding people home. When a waypoint on this polyline is also a turning point (i.e. a textual description to make a turn at this point was returned by the map directions service), haptic feedback is provided in form of vibration upon arrival at this point to indicate that a change of the compass direction has happened. To provide context for haptic feedback, all turning points have been added as overlays to the progress bar in the form of tiny circles. Whenever individuals reach turning points, the progress bar will have advanced to the respective circle effectively synchronizing the vibration with the progress displayed on the progress bar. The final design of the progress bar component can be seen in figure 3.6.

During evaluations, feedback indicating that the app should also feature a landscape mode user interface was provided. Landscape mode support allows individuals to hold the device in any orientation they feel comfortable with. As the API that had to be used in order to receive updates for the device heading does unfortunately not include an option for using the device upside-down, holding the phone upside-down is not supported.



(a) Early design of the progress bar (b) Advanced design of the progress bar

Figure 3.5: Screenshots showing the design evolution of the progress bar

(a) Progress bar when starting the app (b) Progress bar after some progress

Figure 3.6: Illustration showing the final design of the progress indicator

To maximize the available screen area, the status bar is not being displayed while in landscape orientation. When rotating the device, the progress bar adapts and scales accordingly. The final design of the app in landscape orientation is pictured in figure 3.7 and the final design as seen on an iPhone X is pictured in figure 3.8.

As the app may not instantly be ready for use when launched, a black screen featuring a location acquiring animation as seen in 3.9 is used. The icons used for the animation consist of a tilted cross-hair and a location pin. While the initial location of the device has not been acquired, the location pin translates up and down on the y-axis. When it reaches the center of the cross-hair, it moves back to its initial position and the animation repeats until a location could be acquired. To indicate to users that they are not meant

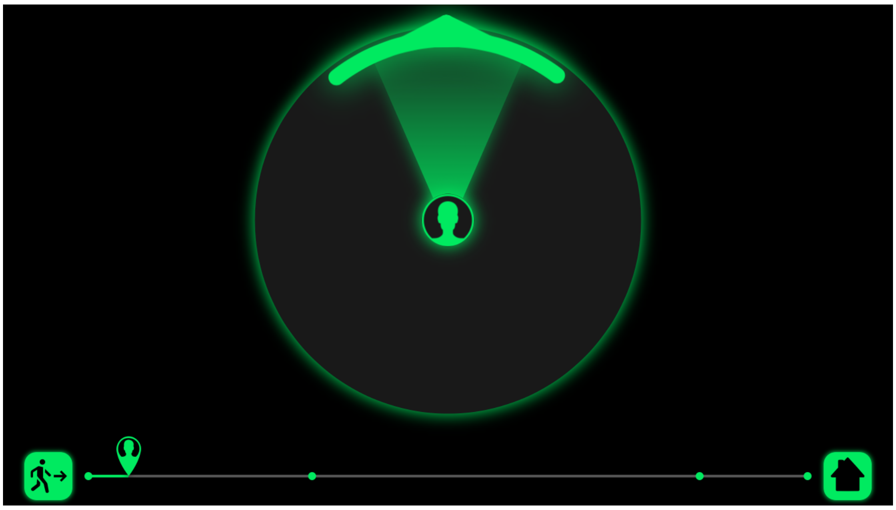


Figure 3.7: Screenshot of the final design of the app in landscape mode

Figure 3.8: Mockup showing the final prototype displayed on an iPhone X

to interact with the animation, an animated iOS system activity indicator is displayed underneath. As the activity indicator is a user interface element that is used system-wide, individuals may be familiar with its meaning.

If launched outside and with GNSS coverage available, the animation is shown on screen only for a very short period of time (e.g. one second). If indoors or if GNSS coverage is not available immediately, it is displayed for a maximum of ten seconds. After an initial location has been acquired and a route has been returned, the primary user interface consisting of both compass and progress bar is faded in and the app is ready to use. The idea behind this approach was to limit cognitive load as no choices have to be made by the user. The absence of any elements that can be interacted with prevents any sudden changes to the user interface and prevents individuals from inadvertently changing settings.

(a) First state of the animation (b) Second state of the animation

Figure 3.9: Illustration showing the location acquiring animation

The last remaining component of the app design is the app icon that serves as a starting point for usage of the app. It can be seen in figure 3.10. The color scheme features a gradient that matches the colors used in the app to provide a subtle reference to the function of the compass. A shade of green was used on the top that represents the compass while pointing towards the correct direction. The icon features a home colored in dark gray to match the overall dark theme of the app and a location marker inside the home to emphasize the meaning of the app.

Figure 3.10: Screenshot showing the final icon of the Take Me Home App

The previous and current sections focused on how the app will look for individuals most of the time. However, the setup process must be completed first in order to use the app and it will be covered in the next section.

3.6 Setup Design

As mentioned in section 3.2, the app was designed to function without any user interaction at all once the initial setup has been completed. The initial setup consists of six screens that guide individuals through the process and can be seen in figures 3.11 and 3.12. A dark color scheme was chosen to match the appearance of the app once set up. Orange was selected as the primary color to ensure good visibility and high contrast.

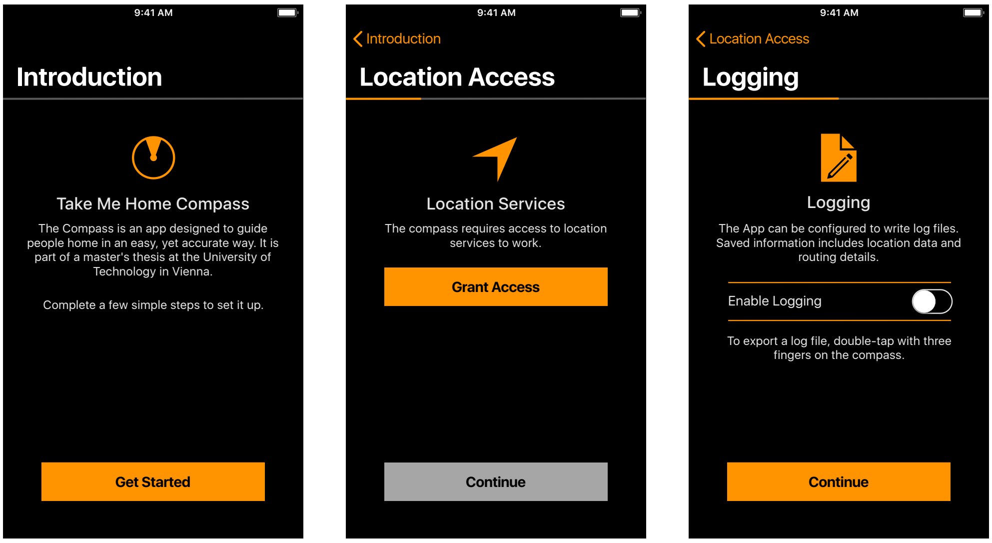
When the app has not yet been configured, the initial screen contains a brief explanation of the app and is pictured in figure 3.11a. The next screen (figure 3.11b) asks for permission to access location services. For iOS, permission prompts are displayed the first time a respective privacy-relevant feature is being accessed after installing an app. As the app does not use location services when it is in the background, only the *While using* access level is required. This prevents apps from accessing location services when not being displayed on screen. After the button labeled *Grant Access* is tapped, an iOS system alert is displayed, querying individuals whether they wish to grant access to location services for the Take Me Home app. In case the request is denied, setup can not be completed as the app can not be used until access is granted in the system preferences. If at any point access to location services is restricted by the user, the app will display this screen again, prompting the user to grant access to continue to use the app.

The next screen (figure 3.11c) contains an explanation of the logging feature and a switch to enable it. It is disabled by default. If individuals want to share log data, they have to initiate the export by themselves. As log files contain privacy sensitive data, they are never shared automatically. The log file is exported as a .txt text file and its content can be viewed before sharing it. Log files are helpful for identifying issues with the app and also allow for the generation of map plots with an accompanying macOS app as will be explained in the next section.

The following screen (figure 3.12a) explains how to set a destination address the compass will point to. In order to select the destination the compass points to, the app provides users with two options. The address can either be entered in a text field or chosen on a map. When an address is entered, search results are presented and subsequently, the address that was selected by the user is shown on a map. During the conception phase, the preferred method of setting the destination address was supposed to be a user's contact details. The benefit of this approach would have been that no manual entry or selection of an address would be required. However, when developing the app, this approach proved problematic as the coordinates returned from the geolocation service could be off from the actual location. In some instances, the coordinates did not correspond to places people would expect the location marker to be at. Therefore it was decided to have the coordinates selected by the user to avoid this problem.

Individuals can select or enter the address on the subsequent screen (figure 3.12b). After a location has been selected, it is displayed on the map for verification purposes and the button for saving the destination becomes enabled.

The last screen, as pictured in figure 3.12c, contains a confirmation that the app has been successfully configured and a reminder on how to reset the app in order to initiate the configuration process again when needed (e.g. for testing purposes or when moving to a new home). To reset the app, a switch has to be toggled in the system settings. This approach has been chosen to prevent individuals from unintentionally resetting the app. It also guarantees that no user interaction will be required once setup is complete.

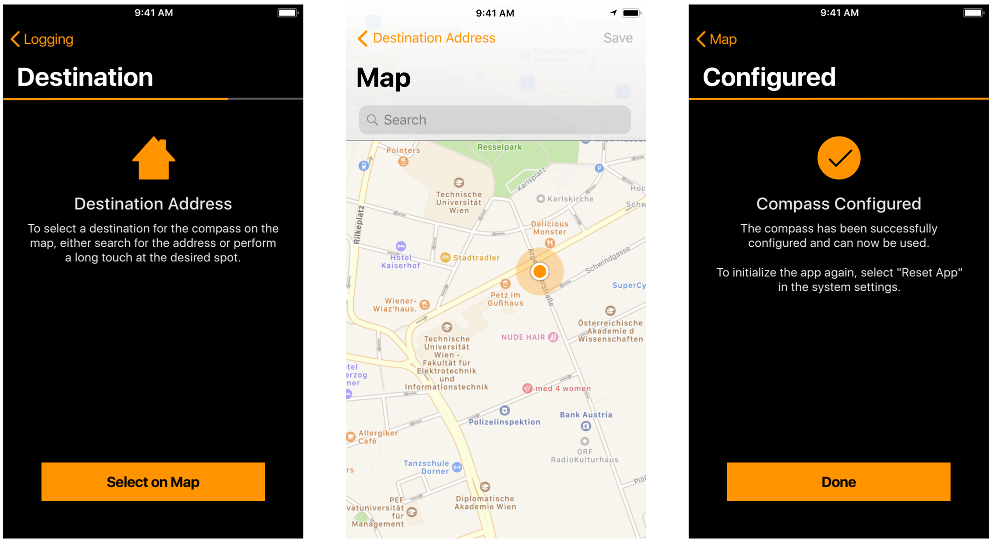


(a) Introduction (b) Location Access (c) Logging

Figure 3.11: Illustrations of the first part of the setup process of the Take Me Home iOS app

A screenshot showing the settings pane of the app in the system settings can be seen in figure 3.13. Permission to access location data has to be set to *While Using* or *Always*. If the permission setting is set to *Never*, the app will not work and will instead show the location permission screen pictured in figure 3.11b without a navigation bar. To allow individuals to confirm whether the app is currently pointing towards the correct destination, the settings include a label showing the current set destination address. To reset the app, the respective setting switch has to be enabled. As the change of the state of a switch has no immediate effect on iOS by design, changes will only become effective when the app is opened the next time. If the switch is enabled when starting the app, all settings will be reset and the switch will be returned to its previous state (i.e. off). The last available setting includes whether to use the Bluetooth prototype device with a PIN being provided that is required in order for establishing a connection to the prototype and it will be covered in the next chapter. When the Bluetooth prototype is used, a location data permission access level of *Always* is required.

This section concluded the design of the app. The next section will focus on limitations that have led to certain design constraints.



(a) Destination (b) Map (c) Configured

Figure 3.12: Illustrations of the second part of the setup process of the Take Me Home iOS app

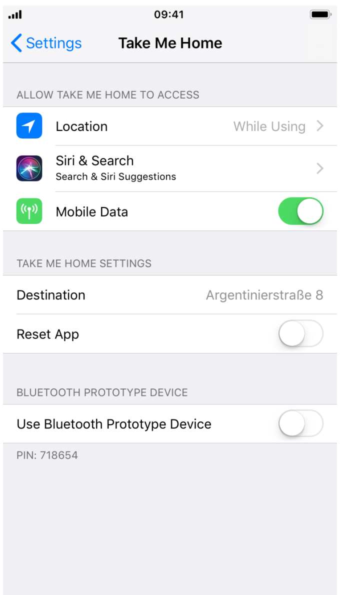


Figure 3.13: Screenshot showing the system settings for the Take Me Home app

3.7 Limitations

As covered in chapter 2, GNSS systems mostly provide accurate data, but there are certain limitations. When used indoors, the reported location of a device is, in most cases, not obtained through GNSS signals but rather through previously recorded WiFi SSIDs or cell tower locations and thus not very accurate. When satellite coverage is not available, the reported horizontal accuracy of a location on iOS is usually 65 meters. As a consequence, the reported location will likely not reflect the actual position of the user. While the app can be started indoors, there may be problems concerning the starting position. Due to this fact, the prototype is designed to be used in outdoor situations only.

In outdoor situations, horizontal accuracy is limited to 5 meters in the best case. The horizontal accuracy is usually reported as 10 meters on iPhones released before 2017 and varies slightly for newer iPhones that were among the first listed as supporting the European Union's Galileo GNSS (i.e. iPhone 8, iPhone 8+ and iPhone X). The horizontal accuracy (i.e. the radius of uncertainty) that is returned by the API is however only correct when there is no interference from buildings. In cities, the radius of uncertainty can be larger than reported.

Aside from the limitations imposed by the hardware, other factors introduce additional limitations: the pedestrian routes returned by Apple's map service do not take sidewalks besides streets into account. As a result, polyline segment points are located in the middle of streets. Depending on the distance to the next point and the number of lanes, this fact can lead to very high deviations when calculating directions (e.g. 90° difference when standing on a sidewalk next to the point in the middle of the street).

To lessen the extent of interference and deviations caused by inaccurate route data, the app advances to subsequent waypoints when the location provided by the device's GNSS receiver lies within 25 meters of the waypoint the app is currently pointing to. To prevent erroneous reported locations from interfering with the routing function in the app, users are required to follow a route exactly(i.e. users must not try to skip waypoints or make assumptions about the route). This restriction can, in rare cases, lead to situations where the app requires users to walk back and then forth along the same portion of a track segment. Without this restriction however, situations could develop that would effectively break the routing function of the app.

Apart from interference and deviations, another problem with directions provided by map services in general is the correctness of the data. In general, it is virtually impossible to have both perfectly accurate and current data due to short-term changes. Inaccurate data can, in essence, introduce the following two problems:

The first problem occurs when progress along the route that was provided is not possible. Potential scenarios include mandatory detours caused by road constructions and temporary road closures, that will basically break the algorithm of the app, and non-existent crosswalks which could lead to life-threatening situations if individuals are not careful when crossing streets. The app never tries to identify user behavior as invalid though. If it is not possible to cross a street where the app suggests to, individuals can walk to the next crosswalk, cross the street and continue to follow the directions provided by the app. As mentioned before, this can in rare cases lead to situations where individuals are tasked to walk back a portion of the way they came. It was decided not to correct this behavior as it occurs only in very specific scenarios and corrections could introduce problems that have an effect on more common situations.

The second problem stems from incomplete data. Whenever routes require users to make detours even though shorter paths are available, individuals may start to doubt the function of the app and start to make their own decisions. This can be problematic as these decisions can occur subconsciously. When individuals start to make their own decisions instead of following a route that was set out by the app, the functioning of the app will be hindered. This specific problem will be covered in section 3.9. Another problem that may arise as a consequence of incomplete data is the perceived lack of usefulness by individuals. Especially older individuals often cite the lack of usefulness as a reason for not using new technologies[41].

Although the limitations covered in this section force restrictions on the algorithms used in the app, a lot of effort has been put into minimizing the effects on the actual user experience. Some of the limitations could only be determined during app testing with the help of log files that the next section will cover in detail.

3.8 Insights from Log Data

The app includes the option of logging positions that are reported by the GNSS receiver as well as routing information. The generated log files have proven invaluable for determining limitations of the app.

During early tests, a distance of 15 meters to a route point was used to advance to subsequent route points. For example, when the route required the user to walk along a four lane street, the app did not register the user walking past a waypoint as the deviation from the center of the street, combined with erroneous reported locations amounted to a continuous offset of more than 15 meters. As a consequence, the minimum distance to a waypoint that is required in order to have the app point to the subsequent waypoint has been increased to 25 meters. The map plot of this particular occurrence can be seen in figure 3.14.

Map plots are generated using a small companion macOS app. Blue pins are used to mark turning points and a darkblue line represents the polyline that was returned by the directions service. Newer versions of the prototype expanded the logging capability of the app to include the moments when turning points were reached. In the map plots, they are marked with cyan pins. Coordinates that were returned by the device are plotted in distinct colors depending on the calculated walking speed between two data points. As studies [42],[43] indicate, the walking speed of humans can, for the most part, be

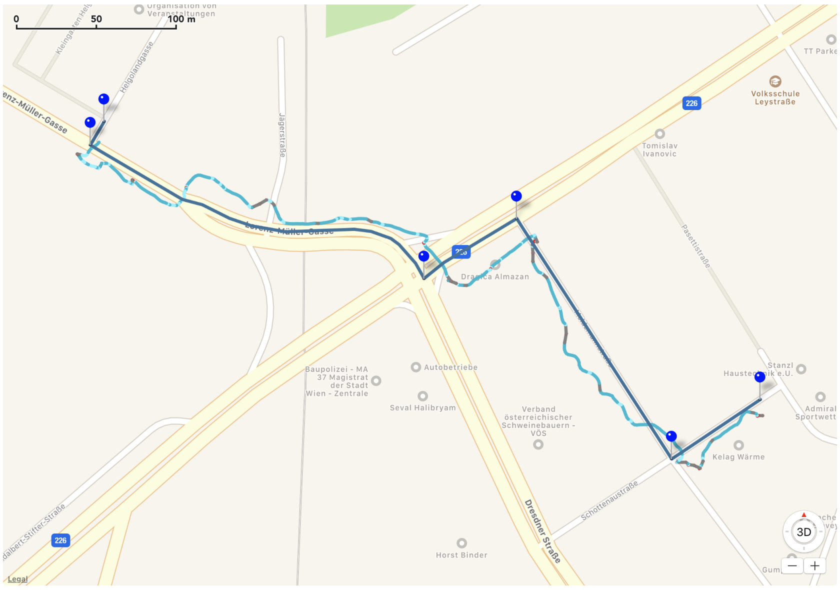


Figure 3.14: Map plot of an early test performed on an iPhone 6s+ with 15 meters required distance from the device to the next waypoint

assumed to be within a range of 2 to 6.5 kilometers per hour. As a consequence, some assumptions can be made based on the log data.

If the calculated speed between two points is greater than 9 kilometers per hour, the GNSS signal likely deviated, thus not allowing for any assumptions about the actual walking speed. The corresponding line segments are therefore colored in gray. If the speed is less than 9 km/h but more than 4 km/h, line segments are colored in a teal color. For speeds slower than 4 km/h but faster than 2 km/h, cyan is used. Segments exhibiting a very slow walking speed may indicate that no movement took place at all and they are colored in red. These segments usually occur when waiting at traffic lights to cross a street. If these segments occur at any other position, there is a high possibility that the individual using the device was not sure how to proceed and had to stop and interpret the situation. To some degree this assumption is also true for cyan colored segments.

As covered in chapter 2 and in the previous section, locations provided by GNSS receivers are only accurate to some extent. An example of how deviations appear when viewed on map plots can be seen in figures 3.14, 3.15 and 3.16. While the three figures contain plots that were generated from log files that were recorded on different iPhone models, the data does not seem to indicate that specific iPhone models perform better or worse in this regard. The amount a signal deviates from the ground truth is mostly dependent on the height of surrounding buildings and the distance of devices to them.

In the next section, implications that these signal deviations can have on the human behavior will be covered.

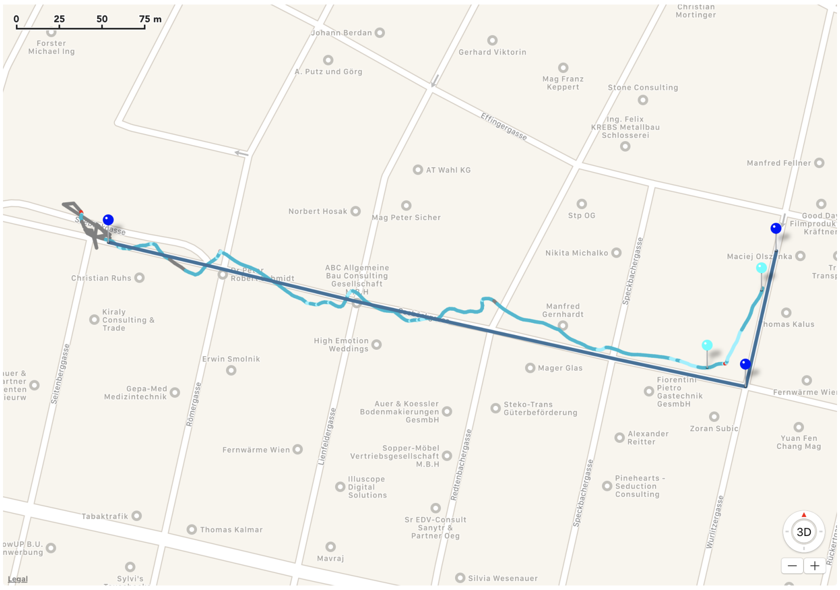


Figure 3.15: Map plot showing GNSS signal deviations during a test performed on an iPhone SE

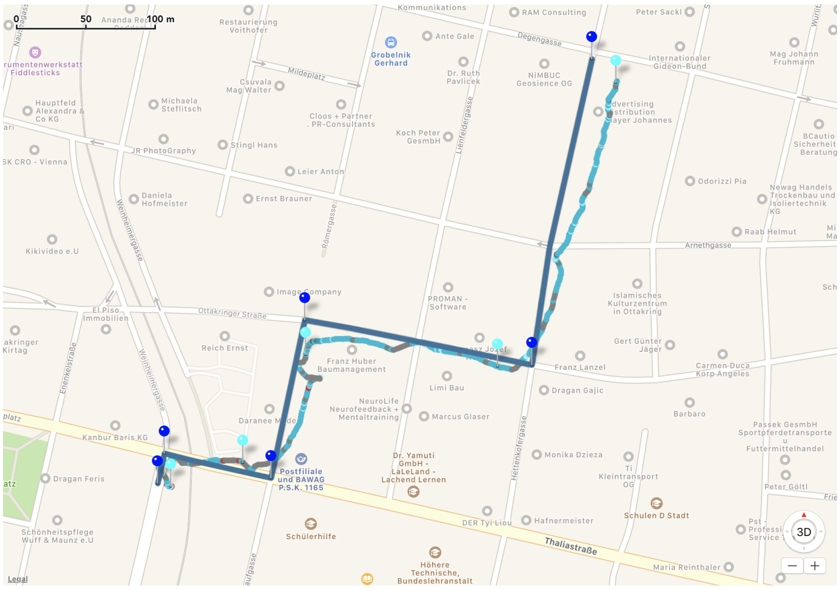


Figure 3.16: Map plot showing GNSS signal deviations during a test performed on an iPhone X

3.9 The Human Factor

During evaluations, it became apparent that there is also a human factor at play: people inadvertently make assumptions when they know details about routes and as a result have a tendency to mistrust the app when it is suggesting directions that appear to make little sense. Because the focus group of this app includes people with cognitive limitations such as dementia and as it can not be ruled out that incorrect data could be generated as a side effect of attempted fixes, it was decided to leave the algorithm as is and place emphasis on the fact that the directions provided by the app have to be followed (that is, if following the instructions is possible and safe) to allow for a faultless experience. As locations that are reported by the device can deviate in every direction and in varying amounts as covered in the previous section, accurate corrections (i.e. accurate in real life) appear to be complicated.

For the plots that were discussed in the last section, the deviations did not have a significant effect on the user experience. During one evaluation however, one participant commented that it is slightly confusing when *the arrow* points somewhat to the left and then somewhat to the right when walking in a straight line. The compass has specifically been designed with the idea of not showing an arrow but an arc that features a triangle pointing up from the middle of the arc to prevent this exact situation. However, the human mind sometimes has a tendency to see complex shapes as smaller parts making up the whole or to accent certain parts[44]. An explanation for this may be that participants are subconsciously being influenced by the compass component being called a *compass*.

3.10 Evaluation

Due to the unusually long and cold winter, no formal evaluation could be performed. The following evaluation will therefore be informal.

Test sessions have been performed with individuals of different age and gender having varying information and communication technology (ICT) skills.

While several individuals tested the app during development on their own phones, an iPhone 6s running the respective up-to-date version of iOS 11 has exclusively been used for the test sessions of the final version of the app covered in this section. An included stock wallpaper has been chosen as a background. To allow individuals to find the app easily, all icons have been moved to other home screen pages. The Take Me Home app icon has been placed as the only icon in the dock as seen in figure 3.17. There was no occurrence of any app crashes.

The method was the same for all evaluation sessions. Destination addresses have been set by the test supervisor to allow for simulating situations of being lost for test subjects. As a consequence, the setup process could only be evaluated after the respective wayfinding sessions. Destinations were chosen within a radius of approximately 0.5 kilometers. Participants were then handed the phone with the task to start the app and to find their

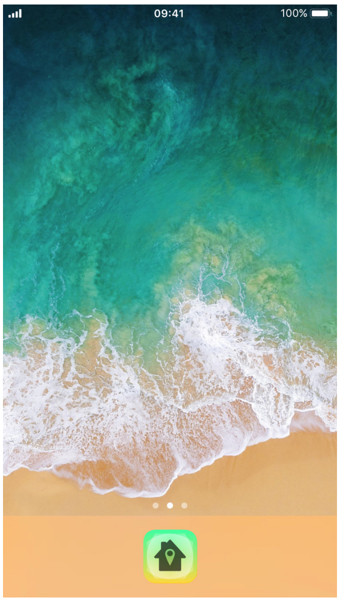


Figure 3.17: Screenshot showing the homescreen layout used for app test sessions

way to the destination. The meaning of the interface elements was not explained allowing participants to draw their own conclusions. Questions regarding functions of the app were only answered after gathering impressions of participants first to collect unbiased feedback.

All participants reached the point where the app displayed the destination address. In general, it can be assumed that the prototype is a success. However, there were some minor issues. One participant interpreted the arc as decoration and only focused on the triangle featured in the middle of the arc, noting that *"the arrow is not very accurate"*. Interestingly, even though this participant misunderstood the compass, there was no problem with reaching the destination. When asking participants about the progress bar, a majority described it as being useful although the connection between the small circles that indicate turning points and vibrations was not made often. A possible solution would be to include a short tutorial as an option.

Test sessions performed in Vienna's first district have shown that narrow streets combined with a low rate of open space can prove to be a challenge. The accuracy of the prototype (analyzed with help of log files) was much worse although wayfinding was still possible. In open spaces, the accuracy was very good, with very low deviations from actual positions. The absence of explicit pedestrian routes (Apple Maps seems to assume that every road and intersection can also be used by pedestrians) was problematic in one test session. The app required the participant to cross a street even though at this specific intersection there was no crosswalk. The distance to the next crosswalk was approximately 100 meters. After assessing that crossing the street was safe, the instructions of the app were followed. The participant indicated that this could become a usability problem depending on where the destination is because if it were impossible to safely cross the street, a detour of 200 meters would have been necessary. During this detour, the app would have remained in the *likely incorrect* state, coloring the compass in orange and displaying turn around arrows.

The orange color used by the app to indicate likely wrong headings was interpreted as implying an instruction to stop by one participant. However, due to the presence of arrows indicating to turn right or left the meaning of the color became clear.

As test sessions was conducted outdoors only, the location acquiring animation covered in section 3.5 was only visible for a brief moment in all cases. When questioned about it, participants mentioned that they did not take notice of it.

As mentioned earlier, participants were asked to reflect on the setup process after wayfinding sessions. To allow the iOS system dialog for granting access to location services to show, the app had to be deleted and installed again using Apple's Testflight platform before handing the phone to participants. The setup process was described as being comprehensible and the number of steps required to finish the setup was not interpreted in a negative way. Afterwards, the app icon had to be placed in the dock again and the app had to be reset to revert the phone to the same state used for all test sessions.

The focus of the next chapter will be the hardware prototype that was developed in addition to the app covered in this chapter.

CHAPTER 4

Hardware Prototype

The focus of this chapter will be the hardware prototype that was developed in addition to the app that was covered in the last chapter. The creative process that influenced many design decisions will be outlined in section 4.1. An overview of the technologies used to manufacture the case for the prototype including explanations of the effects that certain settings can have on printed models will then be given in section 4.2. Section 4.3 will specify the components that were used for the final prototype. The design evolution that led to the final prototype will be the focus of section 4.4. While the hardware prototype does not require individuals to actively use the app, a connection to the app is required in order to leverage the phone's GNSS capabilities and to request a route from the directions service as described in section 4.5. The chapter concludes with the evaluation of the prototype in section 4.6.

4.1 Ideation Process

During the first idea gathering session, one of the main requirements for the prototype quickly became apparent: there has to be some resemblance to the app. This way, individuals would not have to learn how the device works and could switch between the app and the prototype at will. As a consequence, the device will intuitively seem familiar to individuals that have used the app and vice versa.

While looking for ways to represent the main feature of the app, the arc, the first idea involved the use of a display. Unfortunately, OLED (organic LED) displays that have high enough resolution were mostly too small and liquid crystal displays in general did not provide enough contrast to still feature high visibility in direct sunlight. The other problem with these displays was the form: they were all rectangular, which would result in wasted space and introduce size problems, as the arc would have to be displayed large enough to be discernible easily. In addition, micro controllers in general do not have enough processing power to smoothly rotate an image of the arc or to render the arc with glow effects as is the case in the app.

When looking for other options, a suitable alternative was discovered: a ring with 24 RGBW (red, green, blue, white) LEDs that can be addressed individually while requiring only one wire connected to a micro controller. As the ring, in contrast to a display, would not require a rectangular design for a good fit, it was decided to focus on a circular design to match the form of the ring and to give the device a better fit. As a consequence, thoughts about the appearance of the prototype were made. The device had to fit in one hand, therefore there was a limitation concerning the maximum size. Because of the LED ring, the smallest possible size was predetermined.

The required components would also have to include a magnetometer to allow for the same basic working principle as in case of the app. In addition, as the app uses haptic feedback to indicate turning points as explained in section 3.5, the prototype should also feature a vibrating component in order to mimic the behavior of the app.

How the device should be turned on and off was the focus of another idea gathering session. As the inspiration for the software prototype was an analog compass, as covered in section 3.1, the first idea involved a case covering the top part of the prototype that would swing open. The major benefit of this approach would have been the ease of use: when the case was opened, the prototype would turn on and automatically connect to the app allowing for a seamless experience. When it was closed, all power would be cut therefore not only disconnecting from the app but also saving battery power. While this idea seemed to be well suited, there was a disadvantage: the case would have to somehow stay secured when in use while at the same time not being in the way. When not in use, it would have had to open easily, but at the same time it also would have had to stay attached firmly enough to not open by itself. As successfully printing parts that fulfill all these requirements would have proved to be a challenge, a simpler approach was chosen. Instead of a micro switch that would have cut power whenever pressed, a sliding switch will be used.

Power was supposed to be provided by a lithium polymer (LiPo) battery pack. As the target group of the device are people with cognitive limitations, requiring them to remove the battery alongside disconnecting a cable when it was running low seemed inconsiderate. Therefore the device had to feature a charging port to enable charging by simply plugging in a micro USB cable connected to a wall charger or a computer. Later on, when the prototype was already being developed, the idea of using a LiPo battery pack was discarded. The reasons for this will be explained in section 4.4.

As the components can not work without a coordinating component, a micro-controller had to be used. In order to provide the necessary data to the prototype, a connection to the app was required. As the prototype should appear to work independently, using a cable to establish a connection was out of the question. Due to the fact that the app was developed for iOS, Bluetooth Low Energy had to be used. Compared to Wi-Fi, Bluetooth LE has significantly lower power usage[45] and more importantly, does not prevent iOS devices from connecting to the internet when a system setting (Wi-Fi assist) is turned off. The LightBlue Bean was chosen as a micro-controller due to it meeting all requirements, its ease of use and its small dimensions. It uses standard Arduino libraries and can be programmed wirelessly. As a consequence it does not have to be removed from the prototype whenever corrections to the code have to be made allowing for more sophisticated designs.

To keep the prototype simple, it was decided not to include the progress bar as it is basically not necessary for the task at hand. While it would have been possible to include it in some form, it is unlikely that it would have been possible to mimic the appearance of the progress indicator in the app. In addition, the implications of adding a progress indicator would have likely led to a larger and bulkier case design.

While not strictly a requirement, aesthetics are also a very important design aspect of the prototype. If the final prototype has the appearance and feel of an early stage device, it can be assumed that individuals will subconsciously be skeptical of its function. A well built prototype on the other hand can positively influence the opinion individuals have before even trying it out. In addition to the appearance of the device, it is also considered important that the weight is distributed equally to the left and right and that the center of mass is either located in the center or below it in order to prevent the prototype from slipping out of the palms of individuals.

As a last step, it had to be decided how to acquire a case for all these components. While there are a lot of options for boxes that can be bought in stores, it seemed unlikely to find one with the exact dimensions that were needed. Besides, buying a box would likely lead to a design that fits the box instead of a box that fits the design. As the progress of technology allows for easy access to 3D printing, it was decided to use 3D printers to manufacture the chassis. While there are many different types of 3D printing processes, fused deposition modeling was chosen for the majority of the case because of availability, ease of use and previous experience. The specific aspects and difficulties of 3D printing will be covered in the next section.

4.2 3D Printing

As mentioned in section 4.1, 3D printing is readily accessible by now[46]. Of the many 3D printing processes, fused filament fabrication (FFF), also called fused deposition modeling (FDM), is the most common one[47]. The main reason for this is the low entry price of FDM 3D printers. FDM is an additive process and objects are printed in layers by extruding molten material at a temperature of approximately 200 °C in lines. For the prototype, polyactic acid (PLA) filament has been used. The main benefit of this material is its ease of use as no heated print bed is required. In addition, the material is not toxic and can be recycled.

For 3D models printed by FDM printers, the layer height (Z resolution) in general determines the duration and quality of a print. Prints that are considered to be of high quality can be achieved with layer heights of 100 microns (0.1 millimeters) or less. The print resolution on the X and Y axes is determined by the nozzle size.

While 3D printing can be considered common, it is not as straightforward as printing with ink. Unlike traditional ink based printers that in general produce good results from the start, 3D printing requires a lot of tweaking to achieve good results. In addition, the process of creating a 3D model is very time consuming in comparison to creating 2D images. To create three dimensional models, special software has to be used. For this thesis, the used software was Autodesk TinkerCAD[1]. After creating a model, it has to be sliced with another software, in this case Ultimaker Cura[2], to create a set of instructions for the printer so the model can be printed.

In the slicing software, various parameters can be customized that have an effect on how the model is printed. Parameters like print speed, infill percentage and printing temperature for example have a high impact on the outcome and look of a print. An excerpt of settings that have not only an impact on print quality but can also lead to failed prints can be seen in figure 4.1.

Figure 4.1a contains the setting for the layer height on top. *Shell* settings have an effect on how strong the outside of the model will be, with *Wall Line Count* determining the strength of walls. As mentioned earlier, the print resolution on the X and Y axes is determined by the nozzle size. Therefore, a wall line count of 4 as seen in the figure will lead to walls that are 1.6 millimeters thick when using a 0.4 millimeter nozzle. *Top Layers* and *Bottom Layers* affect the strength and look in the Z direction and are multiplied by the layer height. In this case, top layers would turn out 1.0 millimeters thick and bottom layers would come out at 0.6 millimeters. When printing bridges, the amount of top layers has a great impact on the look and strength of a bridge.

Infill Density determines how much of the model (besides walls) will be filled. With 3D printing, it is generally uncommon to use an infill percentage of 100 % (i.e. solid). Lower percentages lead to reduced material consumption and therefore to lower costs however at the price of stability. In general, infill densities of approximately 25 % produce models that are strong enough. If more stability is required, higher percentages can be used. The available infill patterns (not pictured) depend on the software used and can include honeycombs and rectangles.

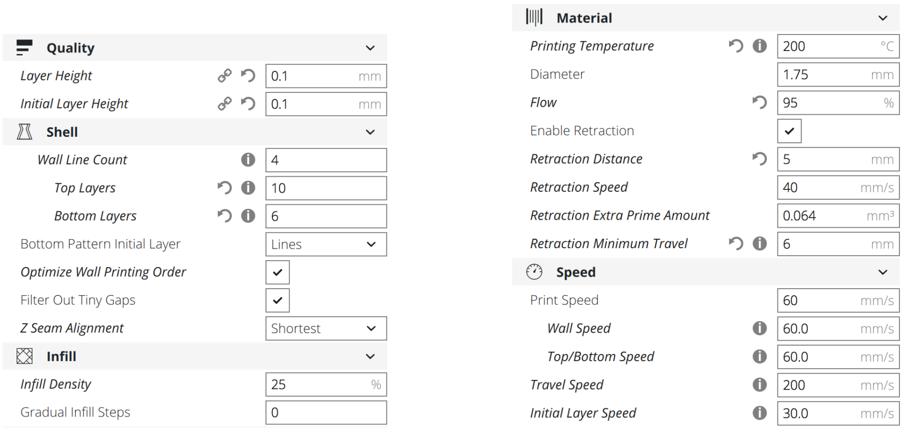
Figure 4.1b contains settings for the material that is extruded and the speed the model will be printed at. The *Printing Temperature* setting is dependent on the used material. For PLA, temperatures around 200 °C are used. *Flow* controls how much material is used while extruding. *Retraction* plays a crucial role in FDM printing. Whenever the extruder is not extruding material (i.e. when it is moving), some molten material will ooze out. If this setting is turned on, the printer will pull back the filament by the specified amount to reduce oozing. When the filament is retracted too often, it can be damaged by the gears of the feeding motor. Therefore it is advised to specify a minimum distance that

[1] https://www.tinkercad.com
[2] https://ultimaker.com/en/products/ultimaker-cura-software

has to be traveled before a retraction occurs. Selective retraction also has a positive effect on the print duration compared with always retracting. The retraction speed and distance vary by printer and have to be determined by trial and error.

Speed settings control how fast the printer lays down the molten plastic and how fast the print head moves. As with retraction, optimal settings vary by printer and, in addition, depend on the model that is being printed. In general, it is advised to use half of the print speed for walls and top and bottom layers to produce better results. As 3D printing is an additive process, the first layer is the most important one and can cause a print to fail early on when wrong settings are used. In the settings pictured, the speed for the initial layer is half of the print speed for the rest of the model.

As there are a lot of settings, at this time it can not be said that 3D printing is ready for general use. In addition, many of the settings can only be determined on a trial and error basis, possibly leading to a lot of frustration because of the results.



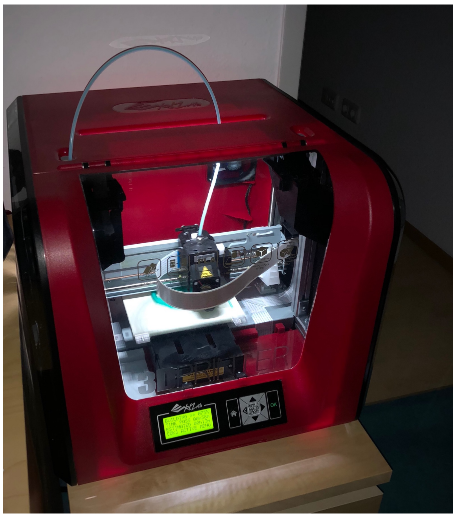
(a) Print settings part one

(b) Print settings part two

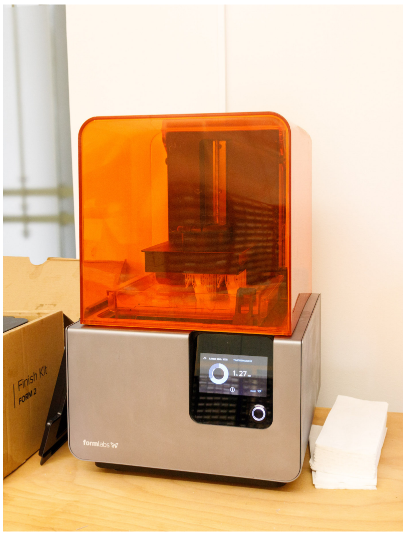
Figure 4.1: Example of 3D printing settings in the software Ultimaker Cura 3.2.1

The case for the final prototype has been printed with a layer height of 100 microns and a 0.4 millimeter nozzle which took roughly 6 hours for all parts. Due to the long printing times, earlier models and parts that are not visible from the outside have been printed with layer heights of 400 and 200 microns to improve the speed of the prototyping process as print quality was not of the essence for these parts. The printer that has been used to print the case is a *XYZprinting da Vinci Junior 1.0 Pro*, as pictured in figure 4.2a. It features a usable printing area of 15 x 15 x 15 centimeters, which was more than adequate for the prototype as it is supposed to fit inside the palm of a hand as covered in the previous section.

In addition, one part of the final prototype that will be featured in section 4.4 was printed with a Formlabs Form 2 printer. Unlike the da Vinci Junior 1.0 Pro that is a FDM printer, the Formlabs Form 2 is a SLA (stereolithography) printer. It uses fluid resin as a printing material instead of a filament that is being molten and laid down.



(a) XYZprinting da Vinci Junior 1.0 Pro



(b) Formlabs Form 2

Figure 4.2: Photos of the 3D printers used for manufacturing

In the next section, the components that were used for the final version of the prototype will be covered.

4.3 Components

As mentioned in section 4.1, the prototype was initially meant to be powered by a lithium polymer (LiPo) battery that was meant to be charged by connecting a Micro USB-B cable to the prototype. Due to reasons that will be covered in section 4.4, the LiPo battery pack has been replaced with three N batteries for the final prototype. As the LightBlue Bean features a battery slot on its back, early designs included a CR2032 coin cell battery for supplying power to it. Because replacing the battery would likely require to disassemble the whole prototype, it was decided to use the same power source for all components. Unfortunately, the LightBlue Bean does not feature a voltage regulator. Due to its operating voltage range of 2.0 to 3.6V, neither a LiPo battery nor three 1.5V batteries could be used. As a solution, a linear voltage regulator had to be added to keep the voltage below 3.6 volts in order to prevent damage to the micro-controller.

Components that were used in the final hardware prototype:

- LightBlue Bean (Arduino compatible, Bluetooth Low Energy)
- Adafruit NeoPixel Ring - 24 x RGBW LEDs w/ Integrated Drivers - Warm White
- Adafruit LSM303DLHC Triple-axis Accelerometer+Magnetometer Board
- Adafruit Vibrating Mini Motor Disc

- Slide Switch
- 3.3V Linear Voltage Regulator
- 3 x N Battery (3 x 1.5V)

To connect the components, jumper wires have been used as they allow to easily swap out single components in case of malfunctions. The wiring can be seen in figure 4.3.

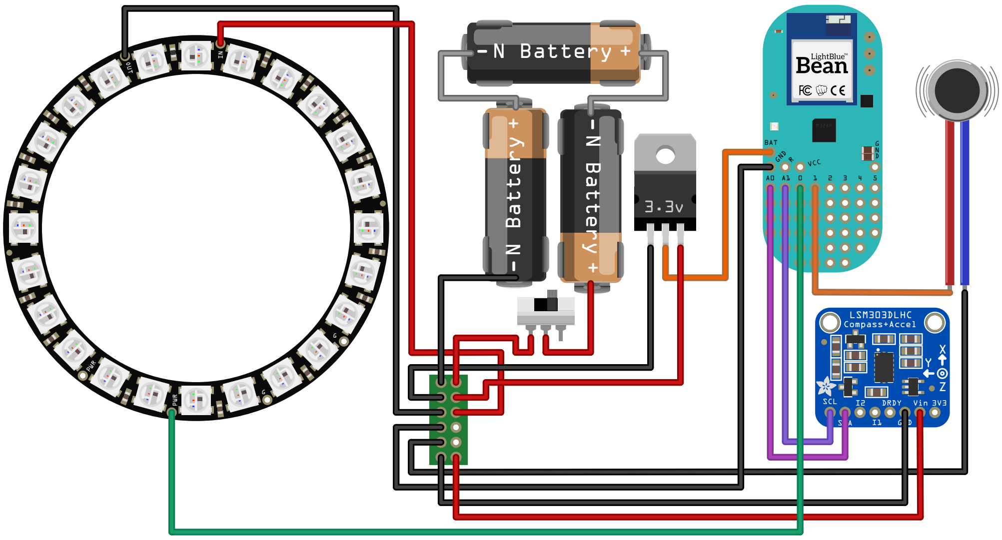


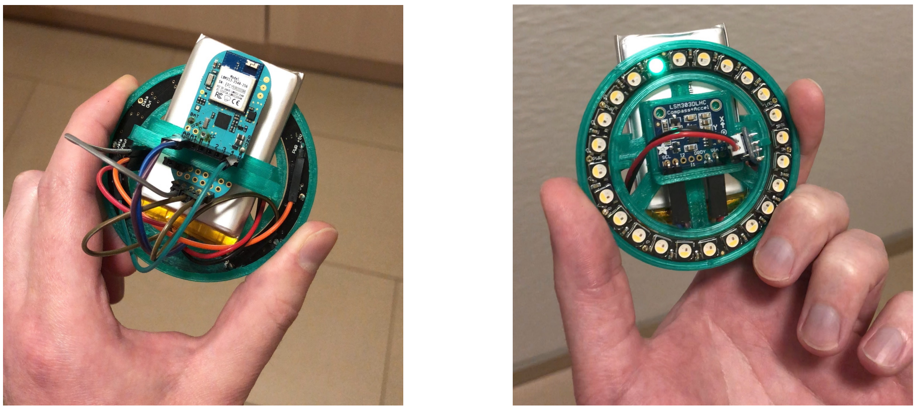
Figure 4.3: Illustration showing the components and connections used for the final version of the hardware prototype

The next section will provide an overview of the design evolution that ultimately led to the final prototype design that uses the components covered in this section.

4.4 Design Evolution

This section will contain detailed descriptions of the design iterations of the prototype. Before starting with the design of the first concept, the parts had to be tested first to determine whether they did work together as expected. This test can be seen in figure 4.4. As the magnetometer had to be calibrated first before a conversion from readings in Tesla to readings in degrees relative to a default vector (i.e. North) was possible, all parts had to be connected properly.

After calibrating the magnetometer to output a tilt-compensated compass heading and therefore determining that the LightBlue Bean was able to fulfill its planned task, work on the first concept for the prototype began. As a side effect, it was determined that the color of the filament used for the early test looked very favorable, as due to its green shade, it conveys a positive meaning while still being somewhat unique and uncommon



(a) Front view (b) Back view

Figure 4.4: Photos of testing whether the components work as expected

in items of daily use. Additionally, the filament did not appear to dazzle in direct sun light due to its transparency.

4.4.1 First Concept

Components used for the first concept:

- LightBlue Bean (Arduino compatible, Bluetooth Low Energy)
- Adafruit NeoPixel Ring - 24 x RGBW LEDs w/ Integrated Drivers - Warm White
- Adafruit LSM303DLHC Triple-axis Accelerometer+Magnetometer Board
- Adafruit Micro Lipo w/MicroUSB Jack - USB LiPoly charger
- 3.3V Linear Voltage Regulator
- Adafruit Lithium Ion Battery - 3.7V 2000 mAh

The first design concept featured dimensions of 84 x 84 millimeters and a height of approximately 25 millimeters. A stacked design consisting of three layers was used for the components, with the LightBlue Bean with soldered headers, the battery and the voltage regulator located on the bottom layer. The battery had dimensions of 60mm x 36mm x 7mm, so it used most of the available space. The bottom layer is pictured in figure 4.5. To separate the next layer from the bottom layer, a lid with holes for the connecting cables was placed over these components to prevent any damage to the battery pack. On this layer, a cut out part of a breadboard with pins soldered onto it to allow for easy changes in the design was used for distributing power. The LiPo charger was also placed on this layer. A hole in the wall of the case was supposed to be used for plugging in a Micro USB-B cable to charge the battery pack. On the third layer, the LED ring and the magnetometer were placed. A wired model of this design concept can be seen in figure 4.6. Also pictured in the background is a failed print of the lid separating the first from the second layer. A cover in the shape of a dome was supposed to cover the magnetometer.

The design was discarded before work on designing the dome began because the wires had a strong springy effect to them that basically stood in the way of designing a case featuring a design that would be as thin as possible while still providing the option of being opened repeatedly.

Figure 4.5: Photo of the bottom layer of the first design concept for the hardware prototype

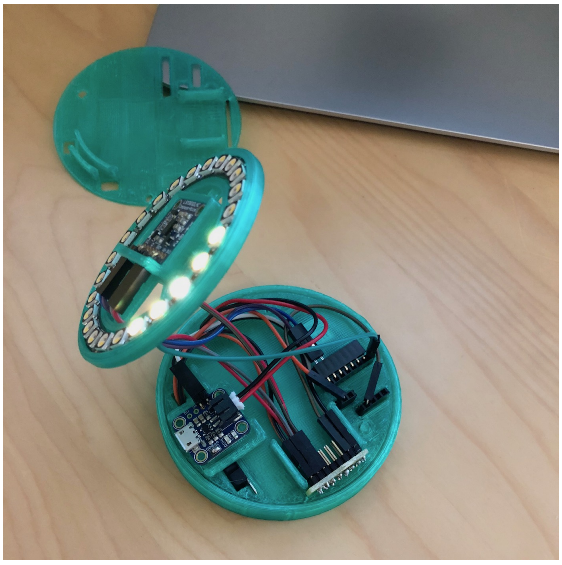


Figure 4.6: Photo of the wired prototype in the first design concept stage

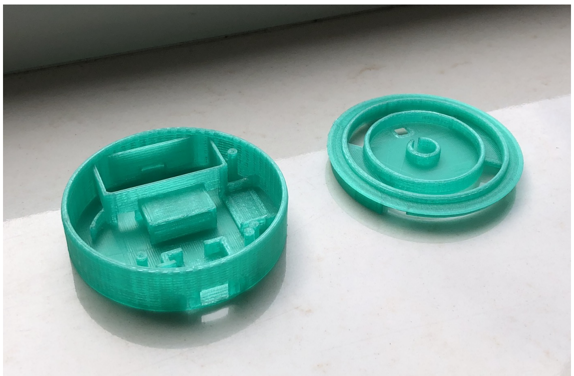
4.4.2 Second Concept

The second concept was largely based on the previous concept and used the same components. The layer system was abandoned in favor of a more sophisticated model that allowed to place the elements independently. The LiPo charger, the LightBlue Bean and the breadboard part were now positioned at the bottom. The cables were routed through a tunnel to prevent them from prying open the case. The magnetometer component was placed inside a recess that was positioned directly above the tunnel that was used for the cables to make use of the empty space. The battery was placed above the magnetometer. The top that consisted of multiple printed parts assembled together housing the LED ring can be seen in figure 4.7a. The model that was used to print the bottom part can be seen in figure 4.8. The battery is colored in light blue.

As the spacing between all components and cables was very tight, multiple attempts at printing the parts had to be made before a model provided a snug fit for everything. While the design was ready to use as pictured in figure 4.7b, the cables attached to the LiPo battery did not withstand the stress that was caused by repeated attempts of creating a perfectly fitting case. As mentioned in sections 4.1 and 4.3, the idea of using a LiPo battery was abandoned. The reason for this will be explained now: while the snapped cables were the reason for the disablement of this particular battery, when looking for a replacement battery, a closer look at the safety notes provided by Adafruit led to a reconsideration of using LiPo batteries in general:

> Additional safety notes: Do not use a NiMH/NiCad/lead-acid charger! Also, do not abuse these batteries, do not short, bend, crush or puncture. Never charge or use unattended. Always inspect batteries and surrounding circuitry constantly for any damage, loose wiring, or possibility of short circuits.[3]

As the device is also meant to be used by individuals with cognitive limitations, it can not be assumed that they would remember to supervise the device while charging. If the device was dropped, the battery could be punctured or otherwise damaged leading to a fire hazard.



(a) The two main parts without components

(b) Assembled

Figure 4.7: Photos of the second design concept for the hardware prototype

[3] https://www.adafruit.com/product/2011

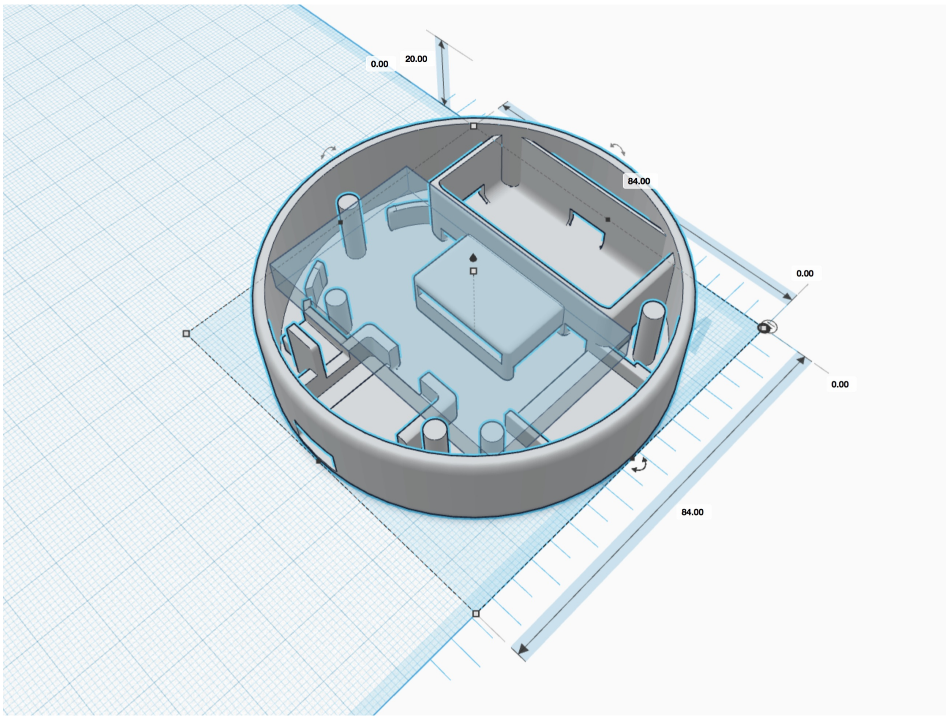


Figure 4.8: Screenshot featuring the case of the second design concept stage of the hardware prototype

4.4.3 Third Concept

Because of the reconsideration not to use a LiPo battery, a new source of power had to be chosen. As all components besides the LightBlue Bean can be used with a voltage of up to 5 volts, a battery pack containing 3 AAA sized batteries was selected. As this battery pack measured 13 millimeters in height, compared to 7 millimeters in case of the LiPo battery, a redesign appeared to be necessary. To prevent the design from getting thicker while keeping the same horizontal dimensions, a new design was developed resulting in a smaller device (featuring a diameter of 73.6 millimeters) that was supposed to be only slightly higher. While working on the design it became apparent that increasing its height only marginally was impossible. The model grew in height with each print and at the end turned out 32.2 millimeters tall as can be seen in figure 4.9. The printed model consisted of two pieces as pictured in figure 4.10.

The LightBlue Bean was supposed to be placed atop the battery case inside the cut out hole of the cover with the magnetometer attached directly to it using angled pin headers. Unfortunately, due to a mix up of the pin configuration, it was discovered that this design would not be able to function at all because the two I2C pins on the magnetometer would have required being crossed and there was simply no room left in the case to do that with jumper wires. As this led to some frustration because solving this problem would not be trivial, the feasibility of the whole concept was questioned.

When holding the 32.2 mm high printed case, it was quickly discovered that it was not comfortable to hold due to its height. In contrast, the part featuring the ring seemed to be a good fit due to being much thinner. In addition, the whole prototype appeared aesthetically unpleasing for the same reason. At that point, it was decided not to try improving this design as it was physically impossible to make the prototype any thinner while maintaining the same diameter. As this design had failed, work on the next concept began from scratch.

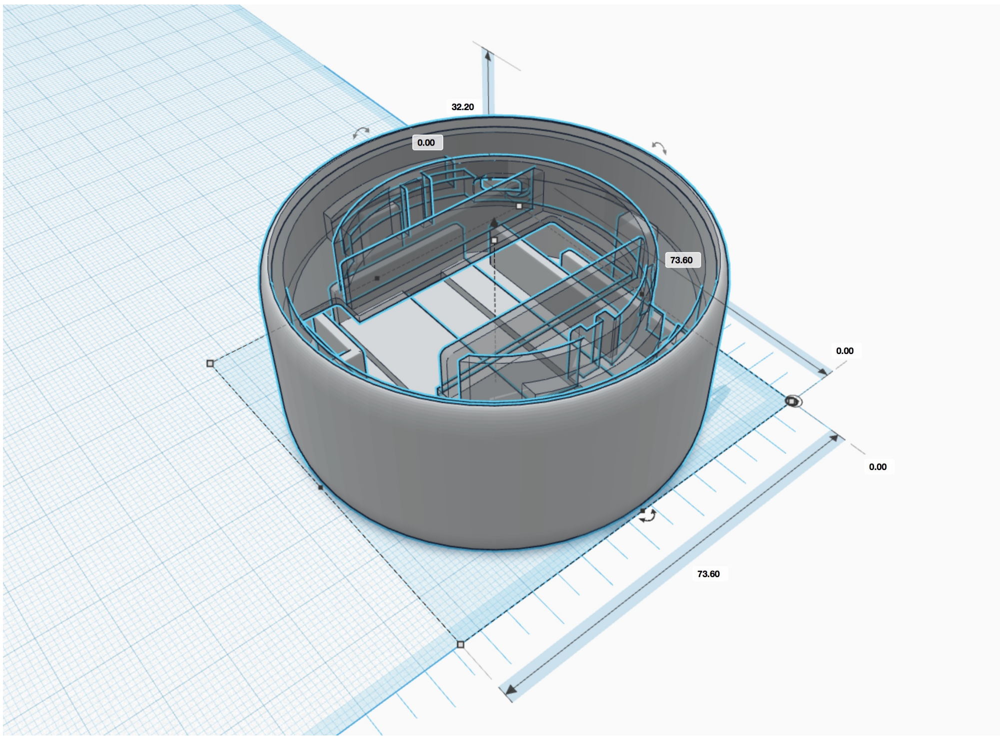


Figure 4.9: Screenshot featuring the case of the third design concept

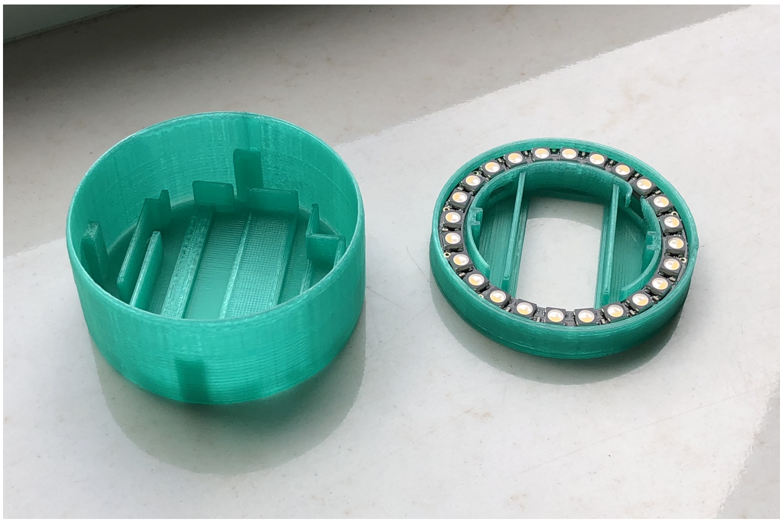


Figure 4.10: Photo featuring the two main parts of the third design concept

4.4.4 Final Concept

The difficulty lies not so much in developing new ideas as in escaping from old ones.
— John Maynard Keynes

As the previous designs did not satisfy certain requirements while basically sharing a similar look, it was decided to start over. Promptly, it was discovered that a cognitive bias was at play: why did the design have to be circular and lead to a model resembling a cylinder? Why were other options not even considered? The bias at play is called confirmation bias. As mentioned in section 4.1, the decision to create a circular design was made very early on. Because the ring housing the LEDs is circular, it seemed logical to also design a circular case. The previous three design concepts progressed in this direction, effectively creating a design resembling a right circular cylinder. As 3D printing is used to manufacture the case, the only limitation on the design is (in general) one's imagination. While certain aspects have to be considered for a model to be printable using FDM printers, it is not a requirement to print the model in one part. As a consequence, various ideas concerning more sophisticated designs have been examined. The final design that was the conclusion of reviewing these designs can be seen in figure 4.11. The components that were used for the final prototype have already been covered in section 4.3. Over the next pages, the decisions that ultimately led to this design will be explained in detail.

Of the ideas examined, the only one that proved viable was a circular design with displaced circular parts of the same diameter as the main circular part cut out on three sides. The idea behind this design can be seen in figure 4.12. The circles all share

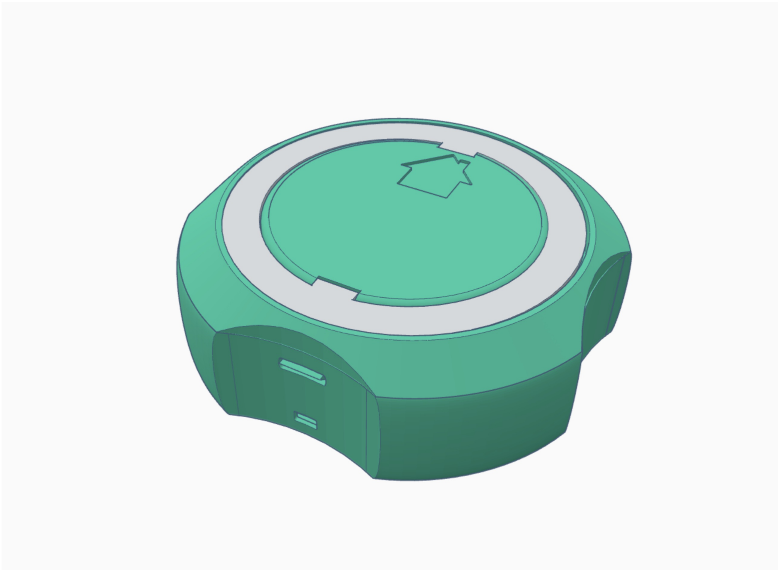


Figure 4.11: Screenshot showing the final hardware prototype design

the same radius of 42.0 millimeters as the first two concepts. The dimensions of the resulting green shape are 77.7 x 80.8 millimeters. The outer walls feature a thickness of 2.4 millimeters and should provide enough stability. As the LED ring has an outer diameter of 65.5 mm, 0.5 millimeters of inner space have been left at each of the three sides to account for inaccuracies that may result from material shrinking while printing.

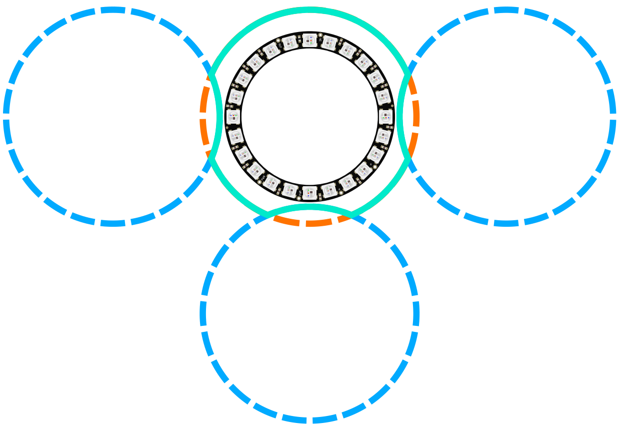


Figure 4.12: Illustration of the shape idea for the final concept of the hardware prototype

In theory, it was assumed that this design would be comfortable to hold and provide the device with a unique look. One of the considerations that resulted in this unique look was to make the device stand out among things that are familiar to individuals. People with dementia may have problems remembering what certain things are for[48]. While in general this is not favorable for the prototype, it should prevent individuals from mistaking the prototype device for something else due to its look. Another important factor that stands in favor of this concept is the fact that the orientation the device is supposed to be held in and thus the top of the device is implicitly conveyed. The two recessed sides (left and right) suggest how to hold the device. The third side would feature the sliding switch used to turn the prototype on and off. Also, due to the recessed design, the switch element does not have to be extended to be operable from the outside. As all of these assumptions were technically wild guesses, a test model has been printed to determine the feel of the concept. In order to reduce material consumption and to achieve a much shorter printing time, only a 6 mm tall part of the model was printed as seen in figure 4.13 to determine whether to continue modeling this design.

Figure 4.13: Photo showing a printing test of the final concept shape idea for the hardware prototype

Judging from the printed test part, the concept seemed like a success as it was very comfortable to hold and its dimensions seemed perfect. It was not too large to be held comfortably while still being big enough to allow for a firm grip. The next step was to rethink the choice of the power source from the third concept as the case housing 3 AAA batteries would likely lead to similar problems. While three separate AAA batteries would fit inside the case, there would be no space left for the wiring. Therefore, it was decided to use N batteries that are approximately 30 % smaller than AAA batteries as can be seen in figure 4.14. N batteries have a length of 30.2 mm and a diameter of 12.0 mm compared to AAA batteries that are 44.5 mm long and have a diameter of 10.5 mm. Both battery types have comparable typical capacities of 800 to 1200 mAh.

Due to the reduced battery size, it was easier to fit all parts and place the wiring. However, it has to be noted that there was not a lot of space left. Compared to the second concept, the designs share a few similarities: the LightBlue Bean is located at the same spot and

Figure 4.14: Photo showing the size difference between an AAA and an N battery

the breadboard power distributor is placed in a similar way. To improve the design and to limit the extent of the height requirements caused by jumper wires, the LightBlue Bean has been adapted: to greatly reduce its height, the coin cell battery holder has been removed along with the straight soldered headers. New angled headers have been soldered to it to allow for a better and tighter fit that would also secure it inside the case once the wires have been connected. The breadboard part for powering all parts is now located besides a battery holder as can be seen in figure 4.15.

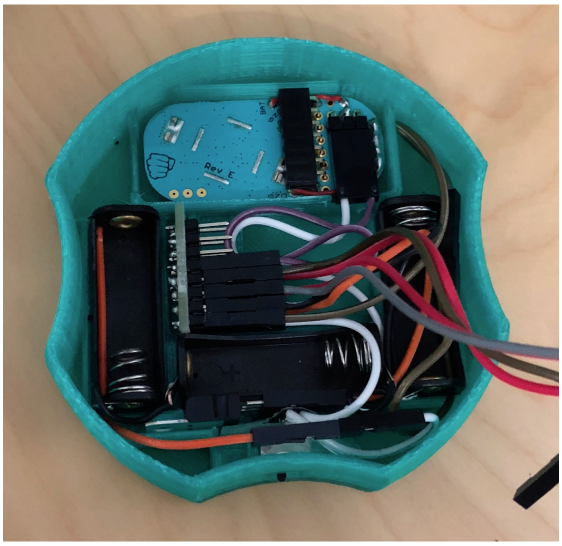


Figure 4.15: Photo showing the component layout of a final design hardware prototype

The batteries can only be accessed after opening up the prototype. While this is not optimal, a printed design with holes on the bottom did not work out. Due to the requirements of 3D printing for FDM printers, it would have proven difficult to create a bottom lid that can be screwed to the case without having the screws stick out on the bottom. As this is only a prototype and not a product that is meant to be mass produced, it was decided to leave access to the batteries as is. However, as N batteries have displayed a tendency to jump out of their battery holders, a cover for the batteries has been designed and printed to prevent this from happening.

As it can not be ruled out that individuals will drop the prototype, all parts fit with very tight tolerances. To prevent parts from moving, several additional parts have been designed that are pictured in figures 4.16 and 4.17. To keep the slide switch in place, a small printed part pictured in dark gray is placed behind it allowing for the wires to go out on top while being secured with the linear voltage regulator that is placed and connected directly behind it. To keep the LightBlue Bean secured, a cover consisting of two parts is placed on top of it. The top part of this cover also serves as the spot for the magnetometer. To keep the magnetometer in place, a cover is then placed on top of it. The assembled case with all covers attached can be seen in figure 4.18.

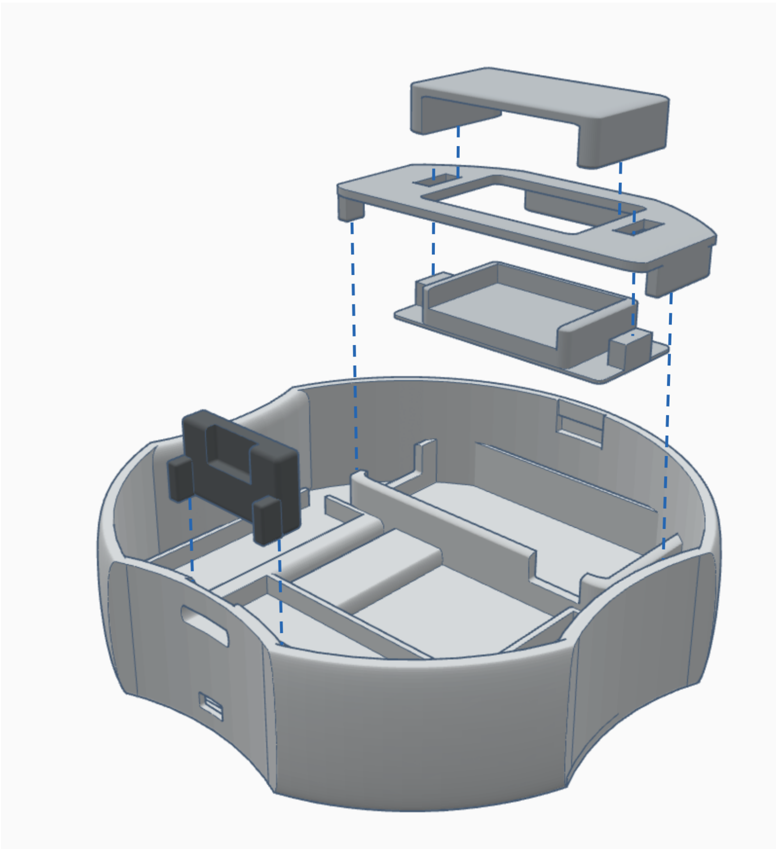


Figure 4.16: Screenshot showing how the various printed parts fit in the final case for the prototype

The LED ring and the vibration motor have been placed in a separate part that can be seen in figure 4.19. While the case form implicitly suggests where the front of the device is, it was decided to include an explicit design element. The same icon representing a

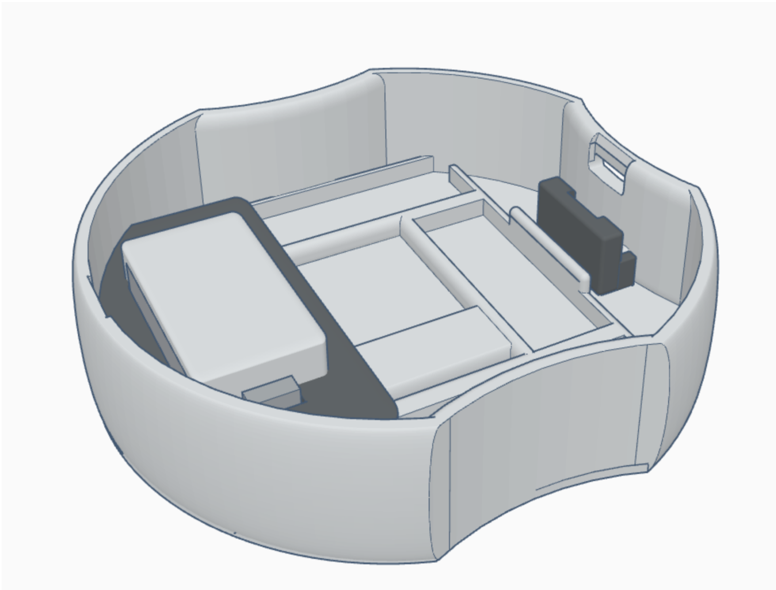


Figure 4.17: Screenshot showing the printed parts inserted in the final case for the prototype

house that is used in the app is also featured on the top part. While testing the design, a cover for the LED ring became necessary as due to their high brightness the light coming from the LEDs was glaring. To add some contrast to the device, it was decided to print this part using another material. As covered in section 4.2, the cover was printed on a SLA 3D printer, a Formlabs Form 2. The printer does not use filament but resin. A transparent white resin seemed like a good choice as it provides enough contrast to the green color the prototype was printed in while still allowing for enough light to pass through. In addition, unlike dark colors, it still provides a positive and friendly appearance. The top part features two snap hooks, one internal and one external that can be used to open the prototype when needed. A photo of the final prototype can be seen in figure 4.20. The weight of the assembled final prototype is 102 grams.

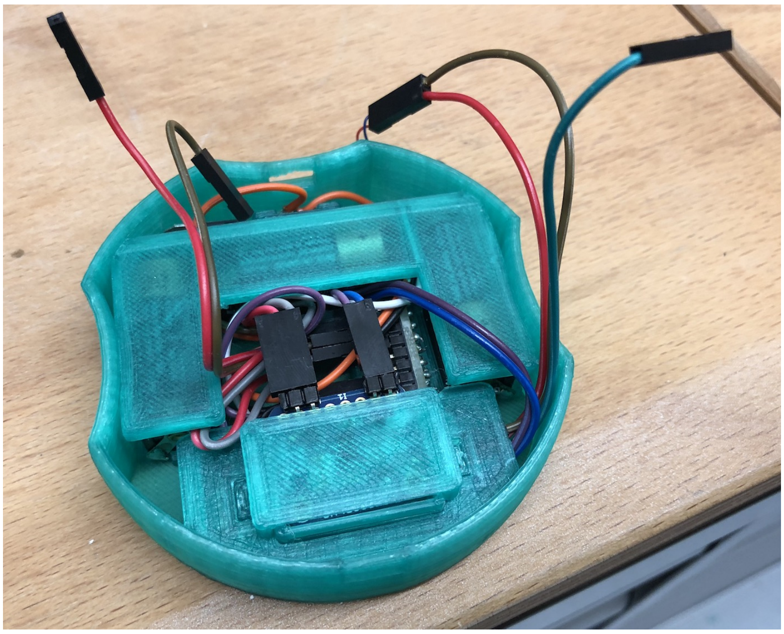


Figure 4.18: Photo showing the final hardware prototype before applying the top part housing the LED ring

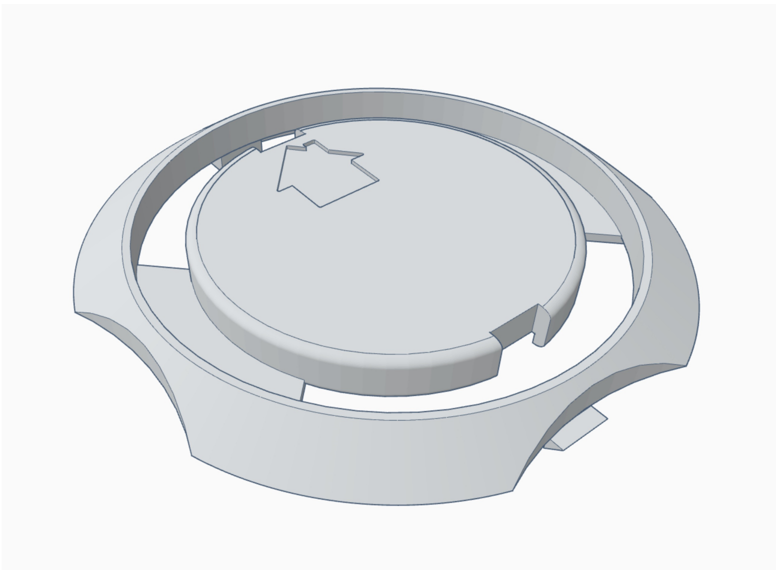


Figure 4.19: Screenshot showing the top part used for the final prototype design

Figure 4.20: Photo of the final hardware prototype

4.5 Connecting to the App

As the final prototype featured a look that was deemed very pleasing, its interaction with the app (or rather the lack thereof) should be implemented in a way that complements its look. As explained in chapter 3, the main idea behind the user experience of the Take Me Home prototypes was to require as little user interaction as possible. In addition, the prototype should appear to work without the app. As covered in section 3.6, the app features a toggle switch in the system settings labeled *Use Bluetooth Prototype Device* (seen in figure 3.13). When this toggle switch is enabled, the app activates functions that are required to interact with the prototype. One of the requirements for usage of the prototype is that the access level for location services for the app is set to *Always*.

The first idea for enabling the functionality required to use the prototype was to include a screen featuring an explanation of the features and a toggle switch in the setup process. After the switch was turned on, the phone would search for the device and start the bonding process after discovering it. As only one prototype was assembled, most individuals testing the app would not be able to make use of the functionality, thus having to skip one setup step. To keep the setup simple, the switch for enabling Bluetooth functionality has been implemented in the app settings.

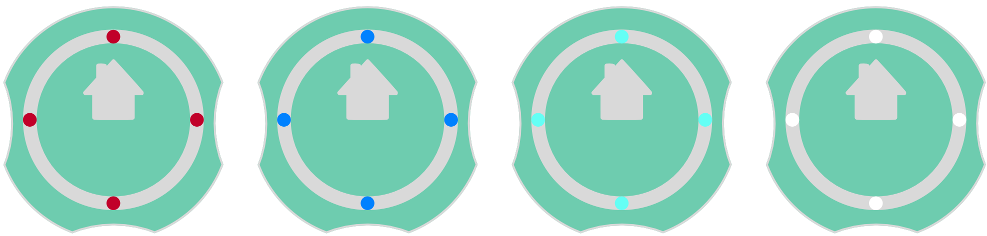
As it can be assumed that the prototype has not yet been connected to the phone, the first step will be bonding. With Bluetooth Low Energy, pairing occurs first which is the process of exchanging temporary encryption keys to establish an encrypted connection that can be used for bonding. Bonding is the process of storing long term encryption keys so the devices can establish encrypted connections without exchanging keys again. After devices are bonded, the connection is encrypted and can, in general, be considered secure. As the app does not share any privacy or security relevant data, no additional encryption has been implemented. To allow for easy testing, the 6-digit PIN number that is used for pairing is predetermined. As only one prototype device has been built, the number can be considered unique. The required PIN to pair with the prototype can be seen in the settings pane of the app right under the toggle switch that is used for enabling prototype device features. In a real world context, the PIN would either be written on a note accompanying the device or included on the bottom of the device.

When the switch is in the active state, the app is constantly searching for the prototype. When it is discovered and not yet bonded with the phone, the standard iOS system popup will appear, asking individuals to enter the PIN code to pair with it. After the correct PIN has been entered, bonding is complete and the app will automatically connect to the prototype in the future without any user interaction.

When the prototype is bonded with the phone and the app is configured appropriately and running, no further steps are required to establish a connection between the prototype and the iPhone. Whenever the prototype has been turned on, the app will request a new route and switch to tracking mode. The simplicity of this approach greatly works in favor of the idea of reducing user interaction to a bare minimum to reduce cognitive load.

Bluetooth Low Energy functions differently from classic Bluetooth. It uses services that inherit characteristics that can be read or written to. Devices can assume one of two roles: central or peripheral. Bluetooth Low Energy devices acting in the peripheral role can also not initiate connections to devices acting as a central but have to wait until a central device initiates a connection. When a device acting as a central has established a connection to a peripheral device, it has to specify which services and thus which characteristics it is interested in. For the Take Me Home app, three characteristics are used. The first is used to write bearing data to the prototype in order for it to calculate where to point to. The second characteristic is used to transfer status messages to allow the prototype to display the current status or to vibrate when a turning point or the destination has been reached. As the iOS system architecture requires a workaround, use of a third characteristic became necessary. While it is possible for apps running in the background to register for location updates, the assertion to continue doing so while running in the background is not made. As the implication of this limitation would require the Take Me Home app to be constantly on screen when turning on the prototype, a workaround was required. The app subscribes to the third characteristic and listens to changes in order to do nothing. While this approach may seem somewhat strange, it does work as the app is woken up by iOS whenever there was an update to the characteristic value and then continues to run in the background for a maximum of ten seconds. The prototype is configured to update the value of the characteristic every six seconds when no data was received from the app to achieve the same functionality as when the app was constantly in the foreground.

As the prototype runs on batteries, it is important to provide an indication for individuals that the device is currently turned on to avoid battery drain. When the prototype is using the LEDs to display an arc, this is of course not required as it should be clear that it is turned on. However, it was necessary to come up with a status indicator for all other cases. To do this in a way that can not be confused with the main functionality, four LEDs representing the four cardinal directions (north, east, south, west) of the device (i.e. the same four LEDs independent of actual orientation) are used.



(a) Not connected (b) Device connected (c) App connected (d) Destination

Figure 4.21: Illustration showing the status indications used by the final prototype

The four states the device can be in besides the compass mode can be seen in figure 4.21. When the prototype is not connected, the LEDs are blinking in red. When the prototype is connected to a device the color used is blue. The reason for this color choice is the fact that the main color used to represent Bluetooth is blue. These two states imply that the prototype is not connected to the app and us therefore not ready to be used without interacting with the iPhone first.

When the prototype is bonded with an iPhone running the app in either the background or foreground, the LEDs blink in a cyan color. This state is kept until the app acquires the current location, asks the location service for directions and successfully receives the routing data. While individuals are outside and in an area with good GNSS and cell phone coverage, the prototype will most likely blink in cyan only for a very short time. This approach was chosen to provide individuals with information on the current status while keeping cognitive load to a minimum by avoiding distractions. The final state is activated when the destination set in the app has been reached. More specifically, when within a radius of 25 meters of the destination as covered in section 3.5. As the prototype does not feature a display to show the home address as in case of the app, the home address could be written on a piece of paper or plastic attached to the bottom or the top of the device. As it is unlikely that people with dementia will often change their home address, this approach should be sufficient and therefore a display is not required.

As it is not possible for the prototype to detect if the app was terminated, a timer is used. When the prototype does not receive bearing data for more than six seconds, the state reverts to *App connected* and instead of the compass, the status LEDs are shown. When the destination is reached, the device disconnects from the phone and stops advertising to prevent the app from reconnecting to the prototype in order to preserve battery power.

4.6 Evaluation

As with the software prototype, due to the long and cold winter no formal evaluation could be conducted.

The evaluation of the hardware prototype was performed similarly to the evaluation of the software prototype covered in section 3.10. Destination addresses have been selected by the test supervisor to simulate a situation of being lost and therefore having individuals not know where they had to go. The device was handed to participants while turned off before asking them to turn the device on and to find their way to the respective destination. As the hardware device may give the impression of being basic when compared to the app and to allow for the gathering of unbiased opinions, some test sessions were performed with individuals that did not have any knowledge about the project and therefore have not used the app yet.

While it has been possible to mimic the apps arc with the LED ring, the effect is very different. The arc in the app does move smoothly and small deviations are therefore hard to see. The device on the other hand uses 24 LEDs, which result in a tolerance of only 7.5° to 15° before switching to the next LED. During evaluations, this has proven to be a problem. It was irritating when the ring switched LEDs constantly while walking straight ahead. During development, the possibility of this behavior resulting in usability issues was considered and a change of LEDs is only taking place when the difference to the previous reading from the magnetometer is more than 10°. Unfortunately, it has proven insufficient in some cases. A better solution would be to diffuse the light so the individual LEDs can not be conceived. While there would still be jumps in the position of the arc, it could prove beneficial when the arc appeared as a uniform shape instead of being made up by five LEDs.

The form factor and the feel of the device were rated favorably by individuals who tested it. Its relatively low weight (102 g) compared to various iPhones (e.g. 174 g for the iPhone X) was also deemed positive. At the same time, it was heavy enough to assert its build quality.

During early evaluations it became apparent that the brightness of the light emitted by the LEDs can be a problem. While the initial setting (approximately 8 % of its maximum brightness) was bright enough during development as it was only tested indoors and in shade, the light emitted by the LEDs was almost invisible when viewed in sunlight. The brightness had to be quadrupled to achieve a relatively good visibility. However, when viewed indoors, the light appears too bright now. When taking into account that the prototype could be needed during nighttime, the light emitted would be dazzling. As there should be no user interaction with the app, including options for adjusting the brightness of the LEDs in the app is not an option. A solution for this problem would have been to use an ambient light sensor to dynamically adjust the brightness.

The vibration feedback has been referred to as being too weak. Unlike the app, the prototype does not feature sounds in addition to the haptic feedback due to the absence of a speaker. A possible solution without adding or changing components includes increasing the duration of the vibration. Due to the brightness of the LEDs however, sudden changes in color (i.e. from green to orange) were perceivable by peripheral vision (i.e. when not looking directly at the prototype) when the top of the device was not in direct sunlight.

Due to use of a magnetometer and only performing tilt corrections instead of complex calculations that are handled by Apple's CoreLocation API in the app, the arc displayed with the LEDs could behave erratically when the device was tilted too quickly. Participants did not regard this being a problem, as the device was held in a relatively static manner without fast changes being made during test sessions.

When compared to the app, the stand-alone appearance of the device was preferred due to the simplicity of only needing to switch it on to receive directions. In contrast, in case of the app, the position of the icon on the home screen could be a deciding factor for finding the app. The absence of some form of a progress bar was criticized by a participant. The person stated that the progress bar in the app raised his confidence in the app and that its absence leaves room for speculation whether the prototype is working as intended.

As the prototype only displays four white LEDs when within 25 meters of the destination as mentioned in the last section and shown in figure 4.21d and due to the lack of a display, individuals had to be briefed that the appearance of four blinking white LEDs constitutes the end of the wayfinding process. For formal evaluations, a label on the device featuring the chosen address could have been included to allow participants to evaluate the complete wayfinding process.

Despite its shortcomings when compared to the app, wayfinding with the device worked just as well as with the app. All participants were able to find their way to the selected destinations.

CHAPTER 5

Résumé and Outlook

This chapter will provide a résumé of the thesis in section 5.1 by briefly covering all chapters and sections. The last section (section 5.2) will conclude the thesis with an outlook on potential future improvements.

5.1 Résumé

This thesis explored the design, implementation and evaluation of two wayfinding prototypes. First, a brief overview of the motivation and the context has been given while also introducing related work. In the second chapter, the state of technology concerning global navigation satellite systems and the problems associated with the technology have been outlined. Chapter 3 focused on the software prototype that was developed. Subsequently, chapter 4 focused on the hardware prototype.

Starting with chapter 1, section 1.1 acted as a starting point for the thesis explaining the motivation behind designing, implementing and evaluating prototypes. As getting lost is something that occurs for everyone with varying frequency, the idea of creating wayfinding prototypes that in contrast to map application (e.g. Google Maps) and analog maps focused on the fundamentals of navigation seemed promising. The prototypes are supposed to be used by people of all ages, with or without cognitive limitations like dementia.

As outlined in section 1.2, dementia is a syndrome that can manifest itself with varying symptoms. Specific symptoms (e.g. disorientation, memory loss) however are common across all types of dementia. Due to aging of the world population, dementia is being diagnosed more often leading to problems concerning public health care systems. Out of the specific symptoms of dementia that had an impact on the design of the prototype, the potential inability of people with dementia to interpret words or numbers had the greatest impact on the ideation process of the prototypes. Section 1.3 introduced the

Way-Key project, a research project following the approach of promoting mobility for people with dementia. Chapter 1 concluded with a summary of a few related projects in section 1.4.

Transitioning from a medical to a technical background, chapter 2 started by outlining the history of global navigation satellite systems, in particular GPS and GLONASS in section 2.1. Section 2.2 included a brief overview of the current state of the GNSS technology. As a conclusion, section 2.3 highlighted potential problems that occur with the current design of the technology.

Chapter 3 started with explaining the inspiration for the software prototype in section 3.1 before moving on to determining requirements and effects thereof on the interaction design in section 3.2. In order to determine a set of requirements, hints from literature on the topic have been taken. The initial design idea quickly proved not feasible, which in retrospection, was a positive experience as it showed how important regular tests can be. Without constantly testing small details, certain limitations or the ineptness of a concept would not have been determined at an early stage likely leading to a waste of time and resources. Section 3.3 gave an overview on the technologies, hardware and software used for developing the prototype.

The next three sections focused on the design of various key components of the app, starting with the compass in section 3.4. As the compass is arguably the single most important part of the concept, the reasoning behind various design changes has been explained in detail including several figures showcasing the evolution of the design. Section 3.5 introduced other parts that make up the app as a whole. As the compass provided little feedback whether actual progress was made, a progress bar has been designed, requiring multiple design iteration before the design proved feasible. To provide users with feedback until their devices acquire an initial position fix, an animation depicting the location acquiring process became necessary as is explained near the end of the section. The section concludes with the design of the app icon which serves as a starting point for the overall user experience. As one of the requirements has been to ensure that no inadvertent changes can be made to the app, a separate setup process became necessary. Section 3.6 provided an overview of the process of initializing the app. Once the app is initialized, no further user interaction beyond opening the app is needed to be guided home.

Certain limitations that have arisen mostly during evaluations of various version of the app were explained in section 3.7. Log files have proven invaluable for determining these limitations as outlined in section 3.8. In addition, it became apparent that a human factor was at play, greatly influencing whether the prototype was seen as feasible, as covered in section 3.9. The chapter concluded with section 3.10 giving an overview on the evaluation of the prototype. As explained, only an informal evaluation could be performed. The results were largely positive although there were some specific minor issues.

The focus of chapter 4 was the hardware prototype that was developed in addition to the app. Starting with section 4.1, an overview of the ideation process for the prototype was given. As the case for the prototype has been 3D printed, a brief overview of 3D printing was given in section 4.2, outlining the impact of settings on the quality of the print (or the lack thereof). Section 4.3 specified the components that were used for the final prototype. As with the software prototype, multiple iterations were necessary before a design was feasible. Section 4.4 covered the evolution that led to the final design concept. Due to the prototype relying on the app, a connection to the app was required as explained in section 4.5. The chapter concluded with section 4.6, covering the evaluation of the hardware prototype that, just as was the case with the app, was only performed informally due to the long and cold winter. The results indicated that the concept can, in general, be considered a success. However, due to the limitations of the hardware used, some issues occurred implying that changing and adding components would be beneficial to achieving a better user experience.

Ultimately, this chapter concludes the thesis with a summary of the thesis in this section followed by an outlook in section 5.2 highlighting potential improvements for future work.

5.2 Outlook

While the last section provided a résumé of the thesis, there is room for improvement which will be covered in this section.

As described in section 3.3, Apple Maps is used as a directions service. At the time of writing, returned routes did not take sidewalks into account. If Apple were to improve their route API, smaller tolerances could be used, resulting in improved accuracy. Routes returned by Google Maps on the other hand did take sidewalks into account. However, a quick test has shown that the data was not always correct as it has apparently been generated automatically. Due to the terms and conditions of the route API, using data provided by Google in the way the prototype currently utilizes route data (i.e. not displaying the results on a Google map), is not permitted. In addition, privacy should be taken into consideration when utilizing services provided by Google.

If the technology used to provide location data (i.e. CoreLocation API that interprets GNSS data) would improve, more precise directions could be provided. Currently, the compass may behave a little erratically due to deviations in the interpreted GNSS signals. The closer the device is to an endpoint of a polyline segment, the more perceivable the effect becomes. While some effort has been put into minimizing the consequences, individuals may still get distracted.

An improved version of the concept could also make use of augmented reality for showing directions as overlays on the stream provided by the camera. Due to the inaccuracies mentioned earlier, this approach would currently require considerate effort and it is unclear whether the targeted user group would be interested in such features and benefit from it. As the goal of this thesis was to create simplistic prototypes, this thought was not pursued further.

For the hardware prototype, potential improvements include modifications to the case allowing to swap the batteries without having to open the prototype. Instead of using jumper wires, permanent connections could be used by soldering wires directly to the components. As a consequence, this would also allow for the use of more common battery types (e.g. AAA) without having to enlarge the prototype. As covered in section 4.6, adding an ambient light sensor to the device could improve its usability in different lighting conditions. Another improvement involves a different cover for the LEDs that diffuses the light and as a consequence would make the arc appear more uniform.

By using custom made parts, the prototype could be made smaller, eventually leading to a device that could be worn on a key ring. Another benefit of this approach would be that individuals would not have to explicitly remember to carry the device leading to an improvement considering that individuals with dementia in most cases also exhibit forgetfulness.

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