Using Augmented Reality and Internet of Things to Improve Accessibility of People with Motor Disabilities in the Context of Smart Cities

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Abstract

Smart Cities need to be designed to allow the inclusion of all kinds of citizens. For instance, motor disabled people like wheelchair users may have problems to interact with the city. Internet of Things (IoT) technologies provide the tools to include all citizens in the Smart City context. For example, wheelchair users may not be able to reach items placed beyond their arm's length, limiting their independence in everyday activities like shopping, or visiting libraries. We have developed a system that enables wheelchair users to interact with items placed beyond their arm's length, with the help of Augmented Reality (AR) and Radio Frequency Identification (RFID) technologies. Our proposed system is an interactive AR application that runs on different interfaces, allowing the user to digitally interact with the physical items on the shelf, thanks to an updated inventory provided by an RFID system. The resulting experience is close to being able to browse a shelf, clicking on it and obtaining information about the items it contains, allowing wheelchair users to shop independently, and providing autonomy in their everyday activities. Fourteen wheelchair users with different degrees of impairment have participated in the study and development of the system.

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The evaluation results show promising results towards more independence of wheelchair users, providing an opportunity for equality improvement.

Keywords: RFID, Augmented Reality, Smart Spaces, Motor disabled people, Inclusion, Retail

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1. Introduction

The pervasive inclusion of different sensors and communication technologies within the city, with the final goal to improve processes, efficiency and quality of life, is the wide framework for the Smart City definition. Overall, the Smart City follows the improvement of the relation between the citizens and their context, pursuing a bottom-up approach of the city. With that goal in mind, all citizens must be able to participate in this new paradigm, regardless of their condition. For instance, motor disabled people like wheelchair users may have problems to interact with the city. One of the main technological actors within the Smart City is the Internet of Things (IoT) paradigm, which proposes including physical objects as a new actor of the Internet, connecting them with people, information systems, and among themselves. However, the use cases of the IoT usually refer to objects with a certain built-in functionality, whether simple, such as thermostats, or complex, such as automobiles. Hence, IoT technologies are a suitable option to improve the inclusion of motor disabled people in the Smart City, due to the pervasiveness of this technology. Currently, around 1% of the world population uses wheelchairs[1] [2]. For instance, shopping at a supermarket is one of the limitations for those who are wheelchair bound. A system enabling interaction with items without reaching them physically would improve the quality of life of these users.

Seldom IoT use cases refer to connecting objects such as products on a shelf in a retail store (garments, food items, etc.) Yet, Radio Frequency Identification technology (RFID) offers a way to connect such otherwise unconnected objects to the Internet, providing a pointer from the physical object and its physical location to a digital "instance" of the object which may include extended information about its characteristics, life cycle history, or even methods that can be called to interact on the Internet. This digital "instance" may be in the form of files (marked up or otherwise), data base registers, data base procedures, SW programs, autonomous agents, or other forms of digital information and/or algorithms. Once an RFID tag has established the link between the physical part of the object (atoms), and its digital counterpart (bits), the foundation is set to develop IoT use cases. One of the use cases of IoT is shopping, that is the retail industry. Online browsing is currently possible for motor disabled people. However, physical browsing like retail shopping or visiting libraries may require of help or assistance of a third person, limiting the independence, privacy and autonomy of that person in everyday activities. Hence, physical browsing is lacking in the context of independent living scenarios, like wheelchair users which are unable to touch or reach the items present beyond their arm's length. For this, they need assistance of another person all the time, that effects their independence, privacy and autonomy.

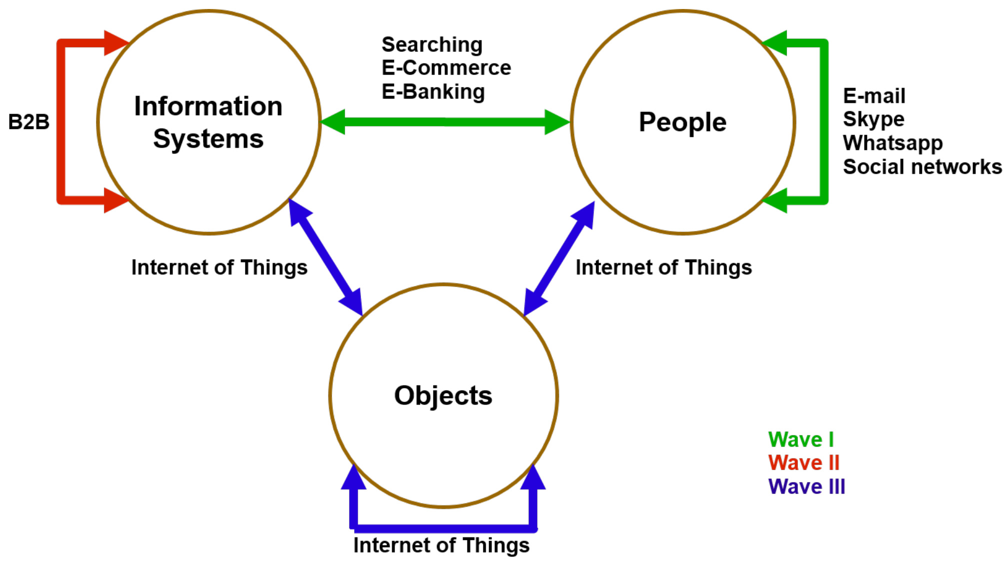

Figure 1: Our research focus is on the interactions between people and simple objects.

Motor disabled people ask themselves about the necessity of using an intelligent wheelchair, when mobility is not fully complete [3]. They are concerned about carrying out autonomous and independent actions, which can be as simple as picking up a small object, without the help of others when they walk freely in adapted spaces. These issues, apparently innocuous, are symptomatic of the design problems in a society that strives for equal opportunities. This situation inevitably affects the human physical, psychological and social well-being. There are numerous side effects, some of which pass through the need to fall back on alternative means of mobility such as wheelchairs. The increasing number of people with motor disabilities require assisting technologies providing increased quality of life to all individuals without exception. Unfortunately, this is currently not the case, since there are many obstacles with technology, requiring many expensive resources or further studies to improve access for every citizen.

In this paper, we present a system that allows wheelchair users with specific degrees of impairment to do shopping and browsing independently, privately and autonomously. Our research is focused on the interactions between people and simple objects as shown in Figure 1. We employed the phenomena of IoT to provide independent shopping experience to people with motor disabilities. Our system is based on Radio Frequency Identification (RFID), Interactive AR and Touchscreen interfaces.

Our contributions in this work are twofold. First, a user study has been conducted on wheelchair users in order to know the feasibility, requirements and possible utilization of the system. The study led us to the categorization of wheelchair users and in shaping their shopping behavior and accessibility issues, and thus, their specific requirements. In this research, wheelchair users with different degree of hand and arm mobility are selected for further research. Second, we propose an RFID-enabled ambient assisted living system including an RFID-based Smart Shelf, and interactive real-time interfaces developed for different devices. The Smart Shelf is able to inventory and determine the approximate location of all the items placed in it, which have previously been labeled with RFID tags. When objects are added or removed from the shelf, or their location is changed, these events are automatically detected by the RFID system, so that the information provided to the user corresponds to the actual state of the shelf. The interactive interface allows the user to know the current present items, their location inside the store and their location on the shelf. Wheelchair users may not find the particular product they want inside the store, since for them it is difficult and a lot of effort to enter inside the shop, to move and to communicate. Considering this scenario, two main interfaces are setup, synchronized with each other. The initial interface is placed at the entrance of the store, to provide users with all the information about the items present in the shop, together with their location. The second interface is designed for interacting with each particular shelf within the store, and is to be used close to the shelf. Finally, the system is tested and evaluated with wheelchair users in a laboratory simulating a real scenario.

Next, we summarize the main milestones reached during this project:

- A preliminary user study on wheelchair users to extract basic requirements for autonomous and independent shopping.
- Design and implementation of interaction methodologies based on RFID-enabled Smart Shelves and different interfaces (including AR technologies and touch screens), intended for users with different degree of motor disability.
- The involvement of 14 potential end users in the requirements definition and preliminary evaluation stages.

This study aims to be a significant endeavor in the promotion of independent and autonomous living among motor disabled people within the context of Smart Cities, thanks to IoT technologies. The number of wheelchair users are increasing due to certain factors such as the increase in elderly population or longer life span of people with motor disabilities. For this reason, it is necessary to increase the social inclusion of wheelchair users in order to maintain a healthy and balanced society. This study aims to provide an opportunity to the wheelchair users to improve their social inclusion by means of independently shopping and browsing shelves. Moreover this study will benefit retailers by connecting the offline and online worlds and bringing online shopping features to the offline retail, not only for wheelchair users, but for all shoppers. Finally, it is worth mentioning that this study presents the limitation in the number of participants. However, up to 14 representative users participated in the different stages of this research, returning consequent results and valuable insights on the topics of technology and inclusion.

The remainder of this paper is organized as follows: Section 2 presents the state of the art. Section 3 presents the preliminary user study, and the system design based on the user study requirements is introduced in Section 4. Section 5 presents the implemented use cases and interfaces used in this research, while the internal system implementation is introduced in Section 6. The systems' evaluation with real users is presented in Section 7. Finally, Section 8 presents the conclusion and future work.

2. Literature Review

Researchers and practitioners are trying to liberate the motor disabled people from dependency. They are working on the improvements of wheelchair by enabling them with high tech resources and providing solutions to improve the social inclusion of wheelchair users. In [4], Biswas and Langdon categorize wheelchair users into different categories based on their hand strength, and evaluate different kinds of interfaces. According to the study, touch screen interfaces score higher than other interfaces. In [5], Chib and Jiang show that a greater degree of mobility, a sense of control, and opportunities to escape the stigma of disability challenge the boundaries between the able-bodied and the disabled. Mobile phone appropriation allowed the management of personal identities and social networks, leading to a sense of empowerment.Kuno et al. [6] propose an intelligent wheelchair that can be controlled by gestures. The authors claim that the number of wheelchair users are increasing and there should be advances by technology means in order to provide autonomy to wheelchair users.

As the technology is advancing, research is focusing on opportunistic interaction modalities and aims to eliminate the digital divide introduced by the obsolete design paradigms [7]. There are some specific disabilities that can prevent the individuals from using common interfaces and computer peripherals. For instance, Kim et al. [8] presented a camera mouse system based on a visual face tracking technique that helps users to interact with personal computers through head and face gestures. An interesting wearable system that can be used by wheelchair users having severe disabilities including hand or arm mobility has been presented in [9]. The system is based on a magnetic tracer for the tongue gestures recognition to control their surrounding environment. The authors of [10] developed a head gesture controlled electric wheelchair and in [11] the same wheelchair is controlled through shoulders gestures. The above work is more focused on the development of technology enabled wheelchairs but no valid or practical approach is provided to interact with the items present in the surroundings of the wheelchair occupant.

A robotic arm, allows the user to autonomously collect a desired object from a shelf that has also been developed [12]. The object's position is calculated by stereoscopic vision, from a camera placed on the shoulder of the user. Although it is an intersing work it is not a practical approach consuming high resources and making it impossible for a wheelchair user to employ it in real life. Another article presents the Robotic system which offers increased control functionality for the disabled users. This robot consists of an electric wheel-chair, equipped with the robot arm MANUS [13].

An interesting work has been presented by Caon el al.[14], proposing different interaction possibilities for wheelchair users through gestures and smartphone. The authors used natural interaction possibilities and the latest available technologies. For gesture recognition the authors employed a *kinnect* camera.

The *Smart Store* concept (or smart shopping) intended to aid customers during the shopping process already introduced specific technologies in the store, providing benefits such as reduction on expenditure time and money [15], value on feedback information [16], and business model improvement [17]. The literature also provides resesearch on smart stores focused on the disabled customer. The Shopping Assistant with interface for wheelchair users [18] presents a use case to help wheelchair users shop independently without the assistance of others. The system proposed an extra cylindrical basket that can be lined with the normal shopping bags for easy transport of goods. It allows wheelchair shoppers to remain on the wheelchairs while shopping. Proença et al. present a system [19] that allows wheelchair users to get access to certain objects present in their vicinity by using computer vision techniques and pattern recognition. While the authors present an interesting system and scenario in order to liberate the motor disabled from dependency, it does not provide a sufficient application in terms of retail and shopping where many similar stock in/ stock out products become impossible to identify with computer vision techniques.

Within the *Smart Store* concept, Radio Frequency Identification (RFID) is becoming an essential part of retail industry because of the possibilities it offers such as automated stock count, localization anti-theft, etc. The tags contain item-based electronically stored identification. Unlike a bar code, the tag does not necessarily need to be within the line of sight of the reader, and may be embedded in the tracked object. RFID provides advantage over computer vision since it can identify individual items without direct line of sight, as well as hidden products. Similar products with little or no difference in their look can also be identified and tracked by RFID, for example clothes of same color but of different size. Moreover, RFID is already being used in many scenarios like retail, thus, providing economic advantage over other solutions like computer vision. As soon as 2004, Roussos described in [20] the benefits of RFID deployment in retail, and in 2006 large retail companies already had RFID deployed in their supply chain [21]. More recently, RFID has proven to provide benefits when also implemented in the stores [22, 23, 24, 25]. A comparison between RFID and other technologies in the ambient assisted living context can be found in [26].

In addition to the increasing commerce value of the RFID market, in recent years many researchers have exploited RFID technology in different domains. RFID technology has also been applied in other domains. Since 2009, two credit-card companies have developed specialized microSD memory cards with RFID modules which embed a passive tag and an RFID reader. Mobile payment can be achieved after inserting the memory card in users' mobile phone[27]. Evaluating touching and pointing with a mobile terminal for physical browsing [28] enables physical browsing via mobile phone. The built system supports browsing concepts like selecting objects for interaction by touching and pointing at them. Their physical browsing system emulates passive sensor-equipped long-range RFID tags and a mobile terminal equipped with an RFID reader.In [29] and [30] a preliminary approach has been presented for wheelchair users to interact with the items on the shelf using RFID, Smart Glass and a smartphone.

Generally for wheelchair users the research is focused more on enhancing the capabilities of wheelchairs and empowering wheelchairs with more technology to enhance more participation of the motor disabled people in the society. However, it is more focused on accessing particular spaces and venues but lacks interaction possibilities with the surrounding environment objects. A valid problem that has been identified in this research is to interact with the items present beyond arm's length reach of wheelchair users. In our research we aim to increase the interacting possibilities with the items present on the shelves, particularly in retail scenarios.

In our approach we employed technologies that are readily available and commonly used in retail and in our daily life. We propose to take advantage of RFID that has already become a major player in retail industry and with minimal resources. We propose the use of AR as it is recommended by previous studies also. The use of AR by disable people is discussed in [31] and [32]. However, the combination of both AR and RFID is a unique step towards a practical solution to wheelchair users to shop independently and autonomously in the context of Smart Cities. Our solution requires minimal resources and less infrastructural changes as compared to previous research related to wheelchair users. By providing a solution with technologies that are already being employed, we aim to reduce their stigma of being separated from the general public [5].

3. User Study on Wheelchair Users

Our goal is to provide independence and personal autonomy to the wheelchair users by allowing them to shop independently in the stores. Our objective includes finding the product in the store, moving easily inside the store, and digitally interacting with the products in the store, including those on the shelves outside arm's length reach. Final acquisition of the product could be obtained through direct assistance from the store staff (after or before purchasing the product). Figure 2 contributes towards the motivation of this study, depicting two wheelchair users who can not reach objects on the upper shelves. For this purpose, a preliminary study has been conducted in order to examine the potential usage of technology by the motor disabled people, as well as their requirements. This study was conducted with the help of the *Vigatans* public residence of motor disabled people in Barcelona, Spain. Different gender and age wheelchair users with different severity of disabilities live in the residence. This residence is supported by the city district government of Barcelona.

Figure 2: Wheelchair users are unable to interact with the items present on the shelf.

Table 1: Users categorization in this study, based on the degree of hand mobility.

Group	Hand mobility	Fingers mobility	Other issues
H1	Regular: able to catch and support any object.	Precise: can point to a small area.	None.
H2	Poor: might have problems catching an object.	Reduced: can point within a large area	May have communication and vision problems.

3.1. User Description and Specification

Hand mobility is key for many of everyday activities, including the interaction with devices and interfaces. The degree of motor disability can be categorized into two main categories with respect to their hand mobility, besides using a wheelchair. The first category (H1) includes users having regular hand and arm mobility. This category would include for instance people who had a car accident, loosing the capacity to walk. The second category (H2) includes those users with poor hand mobility. For instance, elder people or brain damaged due to an accident. People in the second category may also have communication problems (i.e. speaking difficulties). The categories of the motor disabled people on the basis of their hand strength and movements can also be found in the previous studies [33, 4]. Table 1 summarizes the user abilities, based on the above categorization, for our preliminary user study, which included 14 participants in total, with an average age of 45 (six woman and eight man).

3.2. Questionnaire

After categorization of the motor disabled people, a questionnaire regarding shopping and technology was distributed to the participants. The starting point was to confirm participant's willingness to visit and shop at brick-and-mortar stores (or use libraries). The subjects were asked about their shopping behavior, assistance requirements and technology acceptability. The purpose of the initial study was to analyze the subject condition and requirements with respect to shopping and technology acceptability, with the goal of designing solutions covering their needs and requirements. The questionnaire included the following questions:

1. Do you usually go shopping(clothes, books, etc.)? (not online)
2. In affirmative case, briefly explain your experience in the store.
3. Do you shop alone, or do you need assistance (relative, friend, shopping assistant)? In which tasks do you need assistance?
4. How do you imagine technology (i.e. smartphone) could help you in the shopping process in a store?
5. Do you buy online? Why or why not?
6. Are you a regular user of libraries?
7. Do you need assistance in a library (from a relative, friend, librarian)? In which tasks within the library do you need assistance?

Moreover, users were given a comment section to write further about the problems and their feelings while shopping, interacting with people for help and moving in a store or library.

3.3. User Study Findings

Table 2 summarizes the information about the users who participated in the study. Overall, 13 out of 14 subjects have reported that they need assistance in case of shopping and browsing, or visiting a library. Next, we summarize some relevant answers from the study:

- Question 1: "*I don't like to go shopping because I don't like anybody to help me shopping. I would prefer to do it alone.*"
- Question 2: "*I have problems to take objects, even take the money to pay. I also have vision problems, so I can't see small letters.*"
- Question 3: "*I can't move with the wheelchair because there are a lot of people and not enough space (in a store, market, etc.) Moreover I need somebody assisting me, and most of the times they don't want to assist me because of my communication problems.*"

Table 2: The preliminary study provided insights on the participants habits and their relation with the technology.

Subject	Gender	Age	Group	Shopping habits	Tech. acceptability
1	Female	26 - 35	H1	Usually	Yes
2	Female	26 - 35	H1	Usually	Yes
3	Male	36 - 45	H2	Rarely	Yes
4	Male	36 - 45	H1	Usually	Yes
5	Male	36 - 45	H2	Usually	Yes
6	Male	36 - 45	H1	Rarely	Yes
7	Male	36 - 45	H1	Usually	No
8	Female	46 - 55	H1	Rarely	Yes
9	Female	46 - 55	H2	Rarely	No
10	Male	46 - 55	H2	Rarely	Yes
11	Male	46 - 55	H2	Rarely	Yes
12	Male	46 - 55	H2	Rarely	Yes
13	Female	46 - 55	H1	Usually	Yes
14	Female	46 - 55	H1	Rarely	Yes

- Question 4: "*An automatic payment system, without the need to take the wallet out. Also, a big screen in the store entrance showing what's in the store and where.*"
- Question 5: "*I do not trust giving my data on the Internet.*"

It is worth mentioning the responses of two participants, when asked about the system necessity:

Subject 5, said,
"*I do not like asking for help to anyone, unless strictly necessary, such as climbing stairs, or a steep ramp, etc. On the other hand, I am very traditional, and I like to enter the store, and to look at the products live and physically. I would like to adopt technology as an opportunity to be more independent*".

Subject 7, said
"*We need some system for day to day activities, like shopping. For us wheelchair users, technology would help us do shopping by ourselves in any*

store, without needing assistance. That would help in gaining personal autonomy."

We used inductive content analysis to analyze the questionnaire answers [34]. Considering all responses from the subjects we concluded the study in shaping the users needs and requirements into three core points. Although we focused on shopping activities, the same conclusions were obtained for the participants who visited libraries regularly.

- **Feel, touch and information:** Wheelchair users want to perform the same activities as anybody else. They want to go to the physical store and browse, touch and feel the items by themselves. Thus, online shopping, although being an alternative for the participants, is just a complementary activity together with brick and mortar shopping. However, for wheelchair users its a lot of effort to enter inside the shop or library in order to know the availability of an item and its location. For them its worth getting the item information before entering. For instance, whether the item is present or not, and if present, where it is.

- **Independence and autonomy:** Participants answers emphasized they are not comfortable with receiving help all the time during shopping or going to a library, feeling ashamed and shy of asking for assistance all the time. This feeling increases the sense of deprivation and lowers the self esteem among them. Most participants prefer not to go shopping or to a library, if they always need the assistance of others.

- **Technology acceptability:** Participants understand and expect technology as a means to get independence and have their own privacy. They were aware of advanced payment systems (i.e. contact-less cards) and envisioned methods to ease shopping procedures regarding their own issues. Except for three participants who had almost no contact with communication technologies (like computers or smartphones), participants understood technology adoption as a way to improve their quality of life.

The initial user study returned clear needs and requirements from the participants. Grouped in three core points, we extracted the participants general requirements, beyond individual preferences. From their determination to shop in brick and mortar stores, to methods for autonomous browsing, the participants had a clear vision of what they would like to find in a store in the context of the smart city. With the participants needs and requirements in mind, we designed different technological solutions, with the goal to satisfy the user study conclusions. Next, we propose a use case adapted to each participant category (H1 and H2) in terms of motor disability, as well as their general requirements to satisfy an independent and autonomous shopping experience.

4. System Design based on Initial User Study

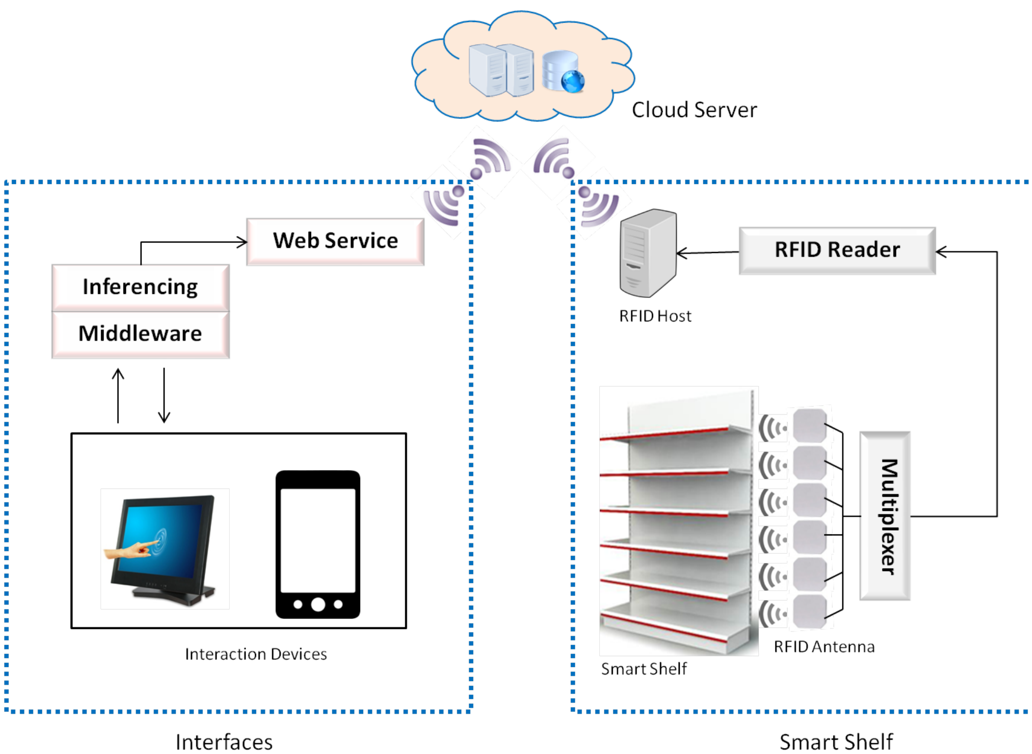

Figure 3: System Overview.

For interaction design, we divided the wheelchair users into two categories i.e. H1 and H2 (cf. Section 3). H1 category represents the users having stable hand and arm movements. H2 represents those who have reduced hand and arm movements, also presenting in some cases communication and vision problems. The knowledge obtained through the initial user study, is used in this section to design and implement a set of technologies specifically adapted to the requirements of each group of participants. IoT technologies like RFID provide the tool to facilitate the connection of objects and information systems in the so called “smart space”, while different interfaces adapt to each group of participants depending on their degree of impairment.

4.1. Smart Space based on RFID System

Wheelchair users benefit from further information about the products in a store, like its availability and location, as extracted from the initial user study conclusions. Hence, a Smart Space technology providing such information on the items in the store is required. We propose the utilization of Ultra High Frequency Electronic Product Code Class 1 Generation 2 (UHF EPC Gen2 for short) RFID [35]. An RFID system is composed of electronic tags (attached to objects), a reader or interrogator and an Information System (IS) managing the system’s operations. This low-cost identification technology is the ”*de facto*” standard in retail since tags are passively powered (no battery required), are cheap (under 10 cents of dollar) and provide item-level identification, being the best IoT technology for such scenario.

We implemented a Smart Space pilot by enabling RFID on a regular shelf with books and DVDs reproducing the scenario in [29]. The resulting system provided the inventory every minute with over 99% accuracy (less than 1 in 100 objects missed at each inventory round), and a space resolution of ∼25 cm thanks to antenna multiplexing. RFID tags of different models from different manufacturers were attached to each product. The front and back view of the smart shelf is shown in Figure 4. A database within the IS stores information about each item including EPC (i.e. ID code), an image (i.e. cover) and all available information on the package. An inventory list, consisting of all objects’ EPCs, together with their approximate locations is periodically uploaded to the database from the RFID system. Details of the RFID-based smart shelf system are shown in Figure 3.

Moreover, a “check-in” touch screen is placed at the entrance of the pilot room, simulating the entrance of a store. The screen is connected to the IS and has access to real-time information about inventory, location (i.e. specific shelf), and product information. This element solves the requirement of all groups of users to have information about product availability without the burden of moving inside the store to end up finding that the required product is sold out.

Figure 4: A) Back of a Smart Shelf showing the RFID System. B) Frontal view of Shelf with RIFD tagged products.

The following interaction methodologies are designed to allow product selection, information extraction, location, browsing and purchasing. Since users may not reach the desired product, item retrieval performed by the store staff, and picked up at check out. Moreover *H1* category users can use the system used for *H2* category users. The user interface design process follows best practices for each category of motor disabled people [36, 14, 37]. We designed the interfaces and selected devices that are used by both able-bodied and disabled in order to avoid stigma of alienation by wheelchair users [5, 32]. This is an important point since using specific technologies makes motor disabled people avoid their utilization. The proposed interfaces can also be user for bridging online and offline shopping by all citizens (impaired and non-impaired) in the context of Smart Cities [38].

4.2. Interaction Method for H1 Category

Motor disabled people classified under the *H1* category have regular hand movement (cf. Table 1). This is the less restrictive group of users, since they have full hand mobility, but cannot reach certain objects without the assistance of another person (i.e. because of using a wheelchair).

Based on the output obtained in the Initial User Study (cf. Section 3), the utilization of smartphones or tablets, together with AR, to access information about products on the shelves is proposed. The user points their device to the shelf, where an AR marker has been placed in the central part, thus mapping physical shelf coordinates to screen coordinates. Moreover, the hand-held device is connected to the Smart Space IS obtaining real-time information about the products on the shelf, and its location within the shelf. By pointing to an specific point in the screen, the system returns the items in that area of the shelf, and a further click on a specific product returns all available information. These devices are nowadays ubiquitous, so user privacy is achieved by letting them use their own devices. Figure 5 illustrates the proposed interaction interface for the *H1* category. Previous studies recommends use of smartphone and hand-held devices for wheelchair users [5, 39].

4.3. Interaction Method for H2 Category

H2 category users have low hand mobility (i.e. shaky hands). Since these users are generally unable to use a smartphone on their own, because of the reduced dimension and required precision for its utilization, same solution as for *H1* group is not possible. Instead, we propose the utilization of a second touch screen next to the smart shelf. Use of touch screen with big fonts and interfaces are recommended in the previous studies conducted on motor disabled people [40, 36]. Figure 6 depicts the proposed interaction interface for the *H2* user group. We stress that *H1* users can also use the *H2* proposed system, as well as people without motor disabilities, enabling smart spaces for the general population in the context of smart cities.

5. Implemented Uses Cases and Interfaces

In order to design the use cases, we considered the offline shopping behavior and life cycle: locating, browsing and purchasing the product are the basis of each implemented use case. We designed these use cases considering the needs and preferences of wheelchair users in the light of the initial study in Section 3, i.e. regarding their degree of hand mobility (H1 or H2). The goal is to ensure a smooth and seamless execution of the shopping life cycle for physically disabled people, as well as for the general population. All the use cases are confirmed by the wheelchair participants. Considering the average shopping environment, and merging it with the wheelchair users' needs different use cases have been implemented which are detailed in the following subsections. These use cases provide each and every necessary step towards digitally interacting with real products located on the shelf, in the context of Smart Spaces.

5.1. Browsing at Particular Location

H1 category users need to point their hand-held devices running the AR application towards the shelf. Then, the user clicks/taps on the screen of the hand-held device, and the information is shown at the bottom of the screen representing the users' clicked area on the shelf. Figure 5 shows the browsing at a particular location through a hand-held device (i.e. tablet or smartphone). If the contents of the shelf vary, these variations will be detected by the RFID system and reflected on the information shown on the screen. If one of the items shown on the screen is removed from the shelf or moved to a different location, it will disappear from the screen. Conversely, if a new item is added to the location being examined, it will appear on the screen. The latency of this changes is bounded by the one minute time resolution of the RFID system in a worst-case scenario.

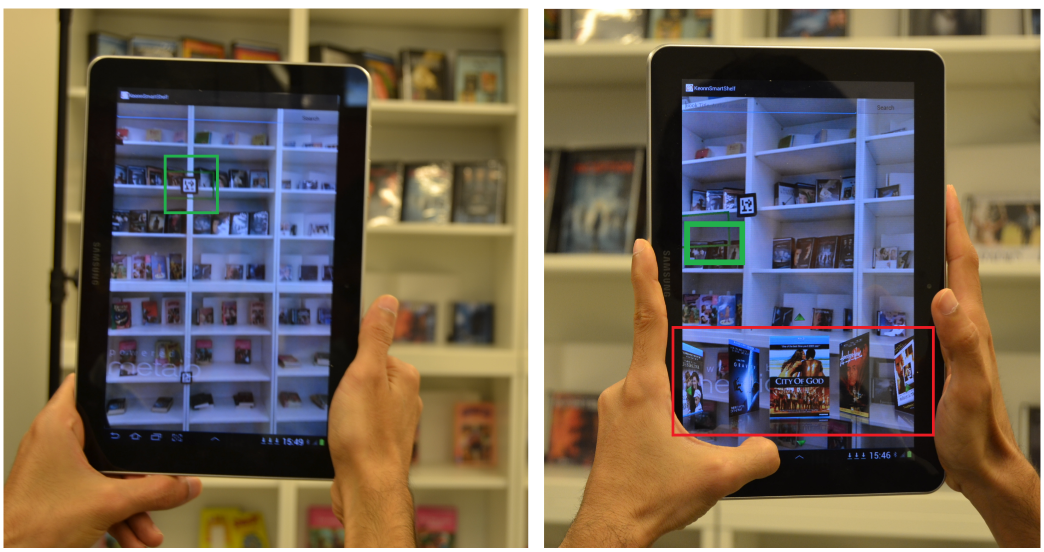

Figure 5: (A) Hand-held device pointing at the smart shelf, where the AR marker is visible. (B) Close up view of the hand-held screen, showing the superimposed item information, and the green square indicating the active area, i.e. the user clicked location.

For touch screen interfaces (category H2 users), the user can browse through web interfaces interacting with the RFID system. The second touch screen is placed near the smart shelf inventorying the products in real-time.

Different categories of the products that are present inside the store and shelf are presented to the user. Figure 6 shows the interface for touch screen.

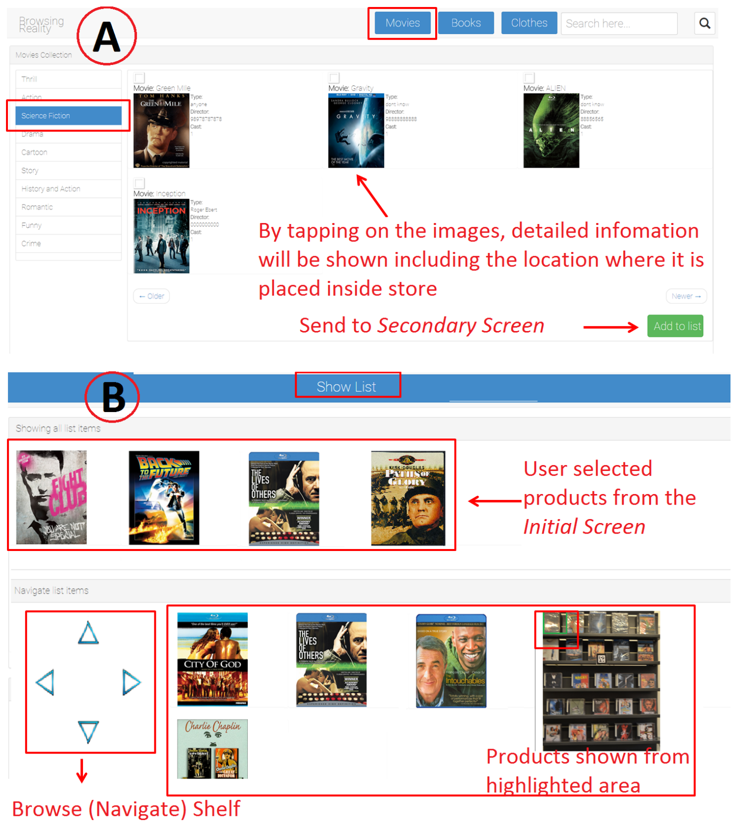

Figure 6: Touch screen Interface

5.2. Navigation: Browsing in Horizontal and Vertical Direction

The user is able to navigate in the horizontal and vertical direction by clicking the arrow images provided. By clicking the arrow images the information about the objects present in the diameter of 20 cm will be shown to the user. The RFID-enabled smart shelf provides the information in real time about the products present on the shelf, together with location information. A green square moves in the user clicked location on the live image of shelf in order to highlight the user area of interest. Figure 8 and Figure 7 detail the process.

Figure 7: Navigate through hand-held device

5.3. Search

A search box is provided to search for products present in the shelf. For hand-held devices, searched product location is provided by highlighting the area on the shelf as shown in Figure 9. Similarly the searched product location is shown to the category H2 users via maps and a green rectangle drawn on a shelf image as shown in Figure 6.

5.4. Selection and Retrieval of Item

At any time the user is provided with the *add to list* icon on the screen. With this icon, the user can keep a list of items to be purchased, then order them and collect them at the counter. The selected item list is constantly being updated at the counter section of the store in real time. The user can call a shopping assistant to retrieve browsed or selected items from the shelf at any time, with the help of assistance icon. After browsing and making the list of interested items, the users are envisioned to use the retrieval functionality

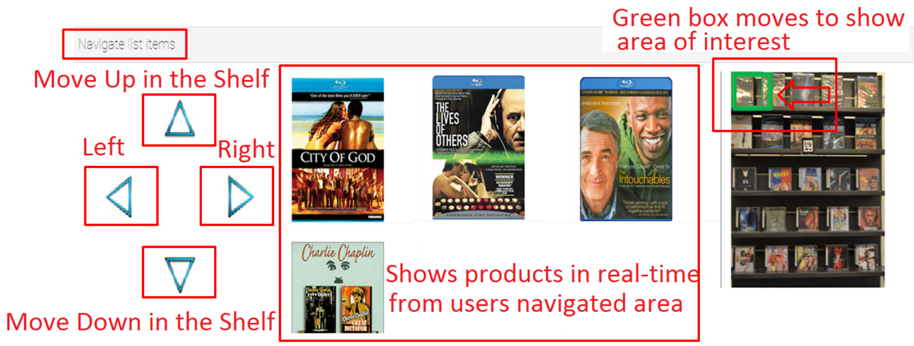

Figure 8: Navigate

depending upon their need (i.e. at the counter or at the same time in front of the shelves).

6. Internal System Implementation

This section details the implementation details of the methodologies and use cases implemented in the project.

6.1. Hand-held based Augmented Reality Application

For *H1* category users, an AR application running on an Android hand-held device is proposed. When the hand-held is pointed to the shelf, it uses an AR marker placed on a known position of the shelf to determine the origin, scale and rotation of the shelf coordinates with respect to the screen coordinates. When a user clicks on the screen, the coordinates of the corresponding shelf position are calculated by the AR application thorough the AR SDK. A web service obtains a list of all the EPC codes that the RFID system has reported as located within a certain distance of such shelf position. A further web service call obtains the information and images of those objects, which are shown by the AR application on the screen. An area of interest referred as green square superimposed on the live shelf image indicates at all times the area about which the information is being shown.

The AR application is developed as an Android application based on the Metaio SDK [41]. The cloud database is built using a Postgres DBMS. The product presence and location information is updated in real time (with the time resolution of one minute as a worst-case scenario, due to the RFID configuration), and if an object is removed, added, or relocated, the change

Figure 9: Search through hand-held device

is updated on the screen. Since RFID technology does not require direct line of sight, information will be shown on the screen about all items in the area, including those hidden behind other items and not directly visible to the user.

6.1.1. System Work Flow

The system is designed in such a way that all the use cases are available to the user in a single interface. The user can search, browse or tap at a particular point from the same interface. The system work flow is shown in Figure 10. Once the user clicks at any particular point or location, the pixels of the user's clicked position are retrieved and passed to the AR SDK in order to get the X, Y and Z axis in 3D space (i.e. the shelf with respect to the AR marker). Then, the axis are translated with respect to the shelf origin. Once the exact location of the user's clicked point is translated to the corresponding point on the physical shelf, the items' information at that location on the shelf are retrieved. After getting the relative item information, an AR interface is constructed for the items. Usually the item is shown in the form of cover flow images. Behind the scenes, the RFID system is continuously inventorying and updating the locations of the items on the shelf. Similarly the browsing in horizontal and vertical directions, along with the search option is passed directly to the coordinate calculation module.

6.2. Touch Screen based Interactive Web Application

Keeping in mind the H2 category user requirements, interfaces are designed with large fonts, buttons and big size images. Touch screens are also chosen since users cannot grab a smartphone, tablet or any hand-held devices. Touch screens at stationary positions are chosen keeping in mind the user ability to interact. Interfaces are designed in HTML5 with Jquery and Javascript. A database is accessed through web services which is periodically updated by the RFID system. Web interfaces provide real-time information about the products presence and location in the shelf and in the store thanks to the RFID real-time inventory update.

6.2.1. System Work flow

The system work flow and architecture is shown in Figure 11. The overall system can be divided into three layers: two layers include the user interfaces and the third layer includes the RFID system and interconnection with the system. All the use case available to the user in the initial screen are connected to the database through web services. The RFID system is also connected to the same database. Once the user performs any action at the initial screen, it is recorded in the database. The second screen interface reflects the same change by connecting to the database through the web services. The web services implements different web methods for both the interface and the RFID system. Both the touch screens and the RFID system are interconnected through the web services and database. The web services are programmed in Java and a MySQL database is used. For browsing inside the store, the interface invokes the *ShowItem* web method that queries database to retrieve all the products of particular category. Once the user selects some product and adds it to the cart, it invokes the *AddtoCart* web method to insert into the database that particular product item, then at the second screen interface show cart action invokes the *ShowCart* web method that quires database to retrieve particular product that user had selected. In this way all the different components and actions of the system collaborate and synchronize with each other. An *Apache Tomcat* server is used for hosting the web service.

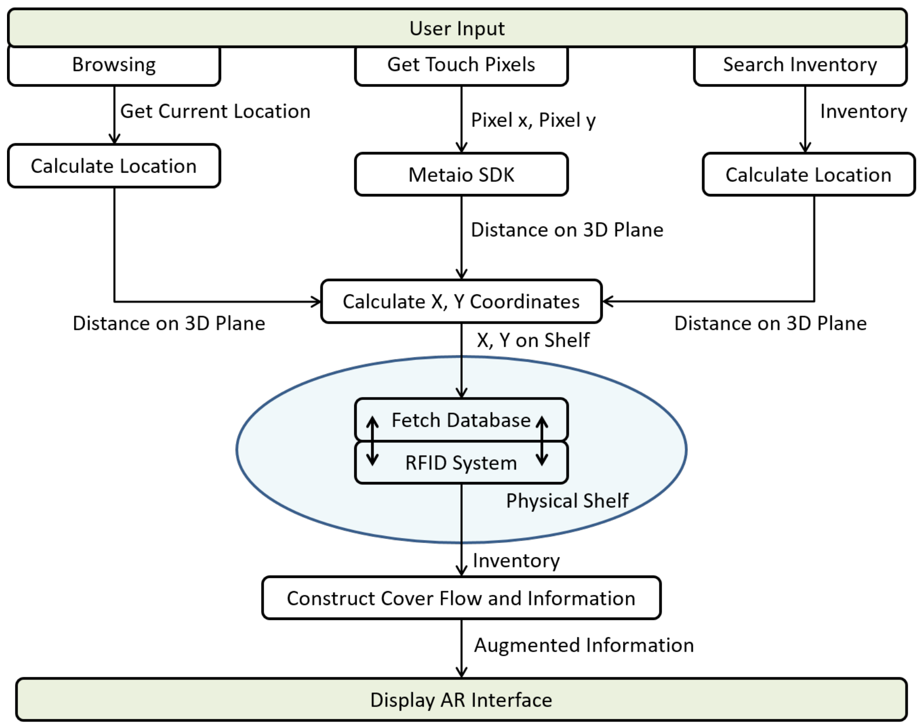

Figure 10: Work Flow for hand-held AR Applications

7. Preliminary system evaluation with users

End user inclusion in evaluation is key to the research success [42]. In order to evaluate the correctness and usefulness of the proposed systems, 9 wheelchair users participated in a pilot, where the use cases implemented in Section 5, obtained after the initial user study in Section 3, were implemented in a laboratory reproducing a section of a store with smart shelves full of products. The smart shelf has a height of 200 cm and width of 100 cm. A total of 150 products were placed on the shelf. These products were DVD's and CD's. Products were stacked in groups of between two and six items, randomly placed on the shelves, so that only the first DVD or CD cover

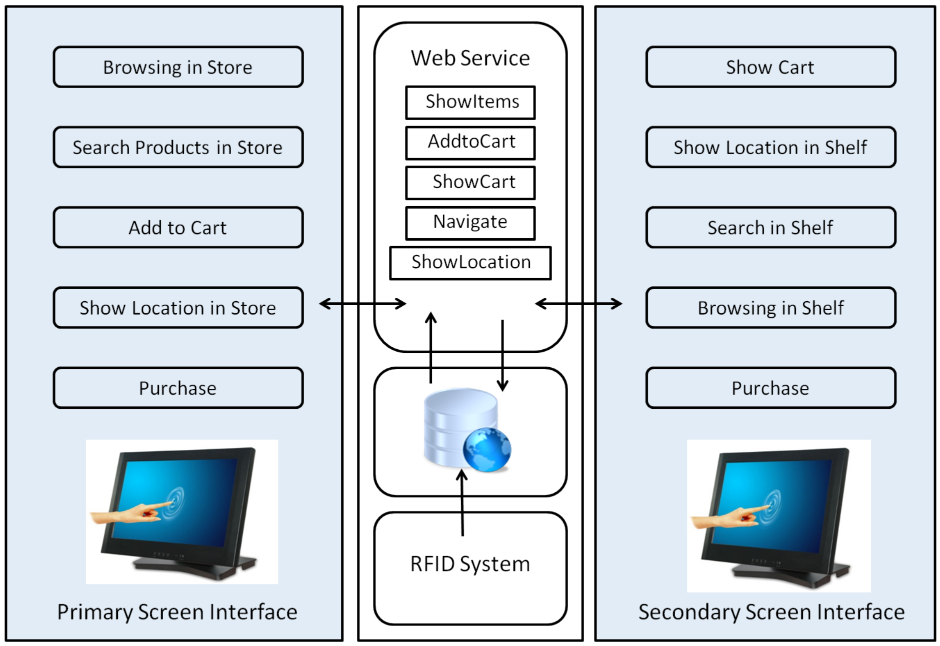

Figure 11: Work Flow for Touch Screen Interfaces

was visible. The remaining four products were hidden from user perspective, however, since RFID doesn't require direct line of sight, it can detect and locate all the hidden products. It is worth noting that the actual participants' activity modified the original products distribution, as it would have happened in a real store. Each participant followed a standard evaluation protocol [43] including:

1. Participants read and signed a consent form.
2. The experiment was explained to the participant.
3. Each user interface was explained to the participant.
4. Participants were given the chance to practice.
5. Participants used the interfaces for a maximum of 30 min.
6. Participants filled a questionnaire regarding their experience.

Throughout the experiment, users were observed by researchers to notice any problem or impediment with the system utilization. The analysis consisted on retrieving both qualitative and quantitative results. Qualitative results rely on observations and participants' opinions. For quantitative results, every user were requested to perform tasks that include the different

Figure 12: Wheelchair User Interacting with the Shelf through AR App

use cases (cf. Section 5): product selection, search for particular product, localization, and purchase a particular product during the usage of the system. Hence, the quantitative results rely on the average amount of managed products per use case. All the tasks were conducted in random order (the counterbalancing principle of usability evaluation [44]). Each user was given 30 minutes to interact with the products and shelf through the interfaces. After using the interfaces and completing all the tasks, each participant answered a final questionnaire, with open and closed questions. The objective was to analyze the satisfaction with each interaction method and interface in terms of easiness, and also to evaluate the efficiency of the interface and the considered features. Overall, we aim to understand whether the proposed use cases allow the users to perform in site shopping, thanks to the Smart Space. We make use of the *Likert* scale [45] with points from 1 (strongly disagree) to 5 (strongly agree). Originally questions were asked in Spanish language that is the native laguage of the region. The questionnaire included the following questions:

1. How do you think this system will help to give you independence in terms of shopping or browsing?

2. Do you think it is useful to you?
3. How easy or difficult was it to visualize and interact with the product information?
4. Are you satisfied with the current level of options?
5. How much did you enjoy using the application?
6. Was it easy or difficult to use the application?
7. Any other comment or suggestion?

The control group participants (C1, C2, and C3), without any kind of motor disability, were asked to perform the same set of tasks that were requested to the wheelchair users, prior to the user study session with the motor disabled people. This control group was used for calibrating the user study (i.e. finding any difficulties not related with the motor disabilities). For both *H1* and *H2* categories evaluation control group had differnt untrained particpants.

7.1. Evaluation Results for H1 category

Individual performance of each participant from *H1* category is shown in Table 3. These results show a performance difference between 2.2 products (number of products searched) and 1.3 products (number of products localized). The results demonstrate that searching or purchasing products with the implemented solution is difficult for people not used to these technologies. However, browsing and localizing products returns a similar performance between the control group and the participants, demonstrating that the participants used the interfaces correctly.

Regarding the questionnaire answers, users were satisfied in general with the proposed system. Most participants gave the maximum score to the different aspects of the system. The minimum averaged score (4) was obtained for Question 4 (*Are you satisfied with the current level of options?*) where participant S7 gave 3 points (average). In the comment section, S7 participant requested to have the system connected to social networks and other online options, which were not implemented in the use cases. The colloective score of the particpants from Question 1 to 6 are 5.0, 4.8, 4.8, 4.0, 4.6, 4.8 repectively on a scale of 5.0.

7.2. Evaluation Results for H2 Category

Individual performance details of each participant are shown in Table 4. In average, the control group obtained better scores, except for product

Table 3: *H1* participants performance during evaluation, with regard the number of products per each use case.

User	Number of products browsed	searched	localized	purchased
C1	6	5	5	4
C2	5	5	4	4
C3	7	5	5	3
Avg. C	6	5	4.7	3.7
S1	5	3	5	2
S6	4	2	3	1
S7	5	3	3	2
S8	4	4	4	2
S13	4	2	2	1
Avg. S	4.4	2.8	3.4	1.6

purchasing, compared with *H1* evaluation. However, *H2* participants scored slightly under *H1* participants in the previous evaluation. The largest difference between control and participants groups for this evaluation are found in product browsing and localizing. On one hand, the differences between control and participants groups is the inverse of *H1* evaluation, meaning that use cases design must follow different rules between *H1* and *H2* scenarios. On the other hand, *H2* participants' motor disability affect their hands and arms (cf. Table 1) and in consequence they are slower than *H1* in performing the same actions. Considering this, the fact that participants performance was close to *H1*'s performance, can be considered as a successful result in terms of human-computer interaction design.

Regarding the questionnaire answers, users were in general satisfied with the proposed system. Question 1 and 2, regarding the overall usefulness of the system, got the higher scores (over 4). Questions 3 to 6, regarding specific questions about the use cases, got slightly slower scores (almost 4). This result demonstrates that although the system behaved correctly, the use cases design was not as well adapted to the touchscreen interface, as comparison with the smartphone or tablet use cases. The colloective score of the particpants from Question 1 to 6 are 4.7, 4.5, 3.7, 3.7, 3.7, 3.7 repectively

Table 4: *H2* participants performance during evaluation, with regard the number of products per each use case.

User	Number of products browsed	searched	localized	purchased
C1	7	5	7	3
C2	8	5	4	2
C3	7	5	5	3
Avg. C	7.3	5	5.3	2.7
S3	4	3	1	1
S5	4	3	3	2
S9	3	4	4	2
S10	4	2	2	1
Avg. S	3.8	3	2.5	1.5

on a scale of 5.0.

7.3. Discussion

This preliminary study presents the limitation on the number of participants. However, in this preliminary system evaluation we collected data from nine representative users within mobility disabled people, divided in two groups based on the participants hand ability. During the evaluation, participants were thoroughly observed. We analyzed that the users felt more comfortable with the smartphone instead of tablet. Handling the tablet, while remaining on the wheelchair was a difficult task. On the contrary a smartphone was easily handled by them. The interaction method we proposed, i.e. to tap on the screen of the hand-held device while focusing the shelf, was feasible and easy to perform. We observed that a smartphone is a better choice than a tablet, as it is easier to handle with a single hand. We noticed some grabbing and handling issues with the tablet by the *H1* category while remaining on the wheelchair. Similarly, issues with the prototypes' UI where detected, to be improved in the next stage of this research. For instance, bigger screens and fonts are recommended for the *H2* participants. During the current experiments we were using 14 inch touch screens. The technologies we used in the system are state of the art technologies and readily available. RFID has already became very common in the the shops and smartphone usage is on the rise. Our system can also be used by the general public for bringing online shopping features to offline retail. The use of the system by general public helps the wheelchair user to feel integrated and equal, providing a step further in the inclusion of citizens in the Smart City context.

Finally, it is worth including some open thoughts from the evaluation participants, regarding their experience and satisfaction with the proposed system:

- *After using the system I can say that it will be beneficial for everyone on wheelchairs because it is necessary for us, and apart from this, all retail (e.g. supermarkets, shops) should incorporate it.*

- *I think the system is interesting, specially for buying products independently. It is interesting to know and get the information of the products that was not possible before.*

- *Current experiments have been done with CDs and DVDs, which is interesting. If the same system would be implemented for shops and supermarkets that include clothing and items we consume every day, it would be great for people in wheelchairs. For day to day activities, and all purchases people do on wheelchairs, this technology help us to attain our independence and maintain our privacy in any store, without needing help, and would result in gaining personal autonomy.*

- *These interfaces are helpful to me to do shopping by myself without asking or requiring the assistance of other people. I would like to have it available at real shops, and that getting used to something like this is very easy, and it is an opportunity to be more independent.*

8. Conclusion and Future Works

The Smart City requires the participation of each citizen in the design, processes and improvement of the city, to implement the desired bottom-up approach. That means no person can be obviated for any reason. Motor disabled people such as wheelchair users cannot participate in some of the daily activities in the city like shopping because of different issues. While online shopping partially solves the products acquisition problem, these users also want to visit and experience on site activities in an autonomous manner, that is, with minimal assistance from others. For instance, wheelchair users cannot look for objects that are not within their arm's length. If they are high on a shelf, or inside a cabinet, or in a pile, it can be very difficult, if not impossible, to find and examine by a person that cannot stand up. The system shows an one step forward towards the independent living of wheelchair users. The evaluation with the representative users and results implies the practicality of the proposed system.

We presented a system including hand-held Augmented Reality (AR) and touch screen interfaces providing real-time inventory thanks to the implementation of Internet of Things (IoT) technologies. Specifically, an RFID-enabled smart shelf, providing information of the products, including the exact location of products in the shelf, was connected to the proposed interfaces. Hence, wheelchair users can use the system to quickly locate and consult items in a store in an independent and autonomous manner. The different interfaces have been designed after an initial user study with real wheelchair users where the requirements of each group of participants have been considered. Finally, an evaluation with real wheelchair users in a controlled scenario returned promising results towards the usability of the proposed system.

Future work includes improving the proposed use cases based on the users evaluation performed in this paper. We also plan to improve the prototype's user interfaces based on the obtained results, and explore alternative means to AR of presenting the items information to customers. In order to simplify the interaction on the tablet a freeze function will be introduced in which user will be able to freeze its point of view and interact with it, without requiring to hold a tablet facing the shelf. Next, we plan the implementation and evaluation of the proposed systems and interfaces in a real store, within the context of a Smart City. That is, providing the users of the necessary information of the products of the store by means of IoT technologies both remotely and in site, to allow any citizen to perform a common daily activity such as shopping, regardless of their condition. Moreover, we plan to extend the proposed technologies to other groups of people with disabilities by adapting the proposed interfaces.

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