# MEDIATED REALITY AND LOCATION AWARENESS TO FACILITATE TOPOGRAPHICAL ORIENTATION

by

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A thesis submitted in conformity with the requirements
for the degree of Doctor of Philosophy
Graduate Department of Electrical and computing engineering
University of Toronto

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# Abstract

Mediated reality and location awareness to facilitate topographical orientation

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Topographical orientation is the ability to orient oneself within the environment and to navigate through it to specific destinations. Topographical disorientation (TD) refers to deficits in orientation and navigation in the real environment, and is a common sequela of brain injuries. People with TD often have difficulties interacting with and perceiving the surrounding environment. The literature suggests that patients with TD are likely to benefit from research leading to clinical standards of practice and technology to facilitate topographical orientation.

In the light of the above, the objectives of this thesis were to investigate methods of realizing a context-aware, wearable mediated environment system for indoor navigation, and to develop a standard method of quantifying the impact of such a system on indoor navigation task performance.

In realizing these objectives, we first conducted an extensive literature review of indoor localization systems. This review served to identify potential technologies for an indoor, in-situ wayfinding assistive device. Subsequently, an automated navigation algorithm was designed. Our algorithm reduced the navigational effort of simulated patients with topographical disorientation while accounting for the physical abilities of the patient, environmental barriers and dynamic building changes. We introduced and demonstrated a novel energy-based wayfinding metric, which is independent of route complexity. An experiment was conducted to identify preferred graphical navigation tools for mediated reality wayfinding guidance. Different combinations of spatial knowledge, graphical presentations and reference frames were considered in the experiment. The data suggested that the locator and minimap are the preferred navigational tools. Two unique optical-inertial localization systems for real-time indoor human tracking were created. The first localization system was oriented to pedestrians, while the second was implemented on a wheelchair. Empirical tests produced localization accuracies comparable to those reported in literature. Finally, a fully operational mediated reality location aware system for indoor navigation was realized. Tests with human participants indicated a significant reduction in physical effort in comparison to the no-tool condition, during wayfinding tasks in an unfamiliar indoor environment. Collectively, the findings and developments of this thesis lay the foundation for future research on wearable, location-based navigational assistance for individuals with wayfinding difficulties.

# Dedication

To my parents Jorge and Lucila, and to my sisters Judith, Yareni and Lucila, who have always supported any endeavor that I decide to embark myself into. To my extended family, who have always been enthusiastic followers of my academic progress. Thanks to Sergio Torres, Pilar Fernández, Fernando Solís, Susana Paz, just to mention a few of my relatives who deserve to be mentioned here.

To my friends in Canada. Jorge Silva, Ana Cano, Manuel Saldaña and Claudia Sánchez, who have been a little piece of Mexico outside of Mexico, making me feel at home when I have most needed it. And Ela Beres, Hugo Bonilla, Sophie Constancias, Carolina Rouleau, Clayton Oliver, Stefanie Blain and Chris Moraes, among a long list of people who should be mentioned here, and I greatly regret to make tacit in the face of space constraints. Thank you all for being my family away from home.

To Rebecca Studin, who has been an enthusiast witness of my life, sharing good and bad moments in the last months prior to the completion of this thesis, which were challenging and exciting.

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To my supervisor, Tom Chau, from whom I have learned important communication and research skills, and whose enthusiasm and energy are a source of inspiration.

To all the people listed here, and many more that I would like to mention, thank you. This work would not have been accomplished without you.

Jorge

# Contents

## 0.1 Acronyms used in the thesis

**AoA** angle of arrival

**BLUPS** Bluetooth and Ultrasound Positioning System

**DS/CDM** Direct Sequence Code Division Multiplexing

**DToA** difference of time of arrival

$E_{RATIO}$ Energy expenditure ratio

**GPS** Global Positioning System

**HMD** Head Mounted Display

**IR** Infrared

**IrDA** Infrared Data Association

**LOS** Line-of-sight

**MERLA** Mediated Reality Location Aware system

**MR** Mediated Reality

**NLOS** Non-Line-of-sight

**OSPF** Open Shortest Path First

$P_C$ Probability of confusion

**PDA** Personal Digital Assistant

**RDS** root-mean-square delay spread

**RF** Radio Frequency

**RFID** Radio-frequency Identification

**RSS** Received Signal Strength

**ToA** time of arrival

**ToF** time of flight

**TD** Topographical Disorientation

**TV** television

**UWB** Ultra-Wideband

**WLAN** Wireless Local Area Network

# Chapter 1

# Introduction

## 1.1 Topographical orientation

Topographical orientation is the ability to orient oneself within the environment and to navigate through it to specific destinations [13]. Through recent magnetic resonance imaging studies, specific structures such as the parahippocampal gyrus [163], parietal cortex [99] and temporal cortical areas [178] have been implicated as neural mechanisms for topographical orientation.

It is generally agreed that in normative way-finding, humans employ a number of different way-finding strategies, including landmark recognition, route learning and map-like (also known as survey) representations of the environment [3]. The particular choice of strategy is dependent on the individualal's developmental age, the familiarity with the environment, the manner by which the environment was introduced, the level of detail in the environment and the specific navigational task at hand.

## 1.2 Deficits in topographical orientation

Topographical disorientation (TD) generally refers to the family of deficits in orientation and navigation in the real environment. Aguirre and D'Esposito (1999) [3] note that difficulties in way-finding may arise from a variety of different cognitive impairments and provide a well-accepted taxonomy of TD. Many different types of lesions and injuries may result in topographical disorientation.

People living with post-traumatic effects of brain injury often have symptoms such as weakness in visual scanning skills, complex attention, prospective memory and sequential processing [90]. These symptoms can lead to problems of interaction with and perception of the surrounding environment, even several years post-injury [36, 145]. It is well recognized that topographical disorientation [179] and spatial navigation deficits [156] are common sequelae of brain injury.

The interruption of blood flow to the brain due to a blood clot (ischemic stroke) or uncontrolled bleeding in the brain (hemorrhagic stroke) is another common cause of diminished cognitive abilities such as memory, attention and topographical orientation [75, 107, 178, 91].

In addition to patients with stroke or brain injuries, topographical disorientation has been reported in patients with Alzheimer's disease [111], transient topographical amnesia [161], unilateral temporal lobe lesions [92], brain tumours such as glioblastomas in the right hemisphere [29] and posterior cortical atrophy [70].

The literature suggests that deficits in topographical orientation can lead to spatial anxiety conditions or wandering behaviours [19, 161, 179]. Consequently, research focused on the development of tools that can be beneficial to patients with TD is required. Wayfinding assistive technologies are examples of such tools.

## 1.3 Literature review of existing studies on topographical disorientation rehabilitation and treatment

### 1.3.1 Motivation

From a survey of the literature, we observed that several research articles in topographical disorientation focus on its etiology, classification or the identification of its neuroanatomical correlates [178, 20, 14, 3, 13, 179], while others present case studies [54, 176, 98].

However, we noticed a paucity of literature on the rehabilitation and treatment of topographical disorientation. Our findings were supported by observations by other authors. Barrash et al. (2000) [14] state that most case studies in topographical disorientation do not assess the patient's condition over time, thereby limiting the capability of analyzing the long-term persistence of topographical disorientation. Brunsdon et al. (2007) [19] remark that aside from their own work, they could only locate one other article, namely a case study by Davis & Coltheart (1999) [33], in which the topic of rehabilitation for topographical disorientation is addressed.

Therefore we decided to conduct a survey of the existing literature on the field of TD rehabilitation to confirm the suspicion that there is at present paucity of literature on the rehabilitation and treatment of topographical disorientation.

### 1.3.2 Article selection and inclusion/exclusion criteria

A search was conducted, looking for peer reviewed articles related to 1) topographical disorientation, topographical amnesia or topographical agnosia, which presented evidence of rehabilitation after one year, or 2) research presenting systematic treatment and rehabilitation techniques for topographical disorientation. To this end, we defined the following inclusion criteria, the article must:

1. Focus on topographical disorientation or any condition related to it (for instance, spatial perception or wayfinding difficulties); and
2. Present evidence towards the development of a treatment of the condition, and
3. Have been written in or translated into English, French or Spanish.

We conducted a literature search for articles published after 1998 in three academic databases, namely PubMed, Scopus and MedLine. Specifically, we searched for the words “topographical”, “(dis)orientation”, “wayfindig” and “navigation” in proximity to the words “rehabilitation”, “treatment” and “therapy”. In combination, this search returned 108 articles (up to June, 2007). However, many of the retrieved articles did not have any relationship with topographical disorientation or any related conditions, and some of them were related to topographical disorientation, but they did not address the rehabilitation or treatment for topographical disorientation. Hence, only five articles matched the inclusion criteria. In the next section we present a survey of the articles selected.

### 1.3.3 Review of selected studies

Grossie et al. (2007) [56] report a case study of a patient with difficulties navigating in unfamiliar outdoor environments. The patient was known to be clever at selecting optimal driving routes prior to onset of the condition. At onset, the patient did not present with any other cognitive disability other than mild deficits in spatial and constructional abilities. The patient’s condition was monitored for three years, accompanied by psychometric tests and MRI, PET and EEG studies on the patient at different stages. The condition of the patient degenerated over time, initially presenting difficulties to navigate in unfamiliar environments, progressing to difficulties in navigating familiar environments, and finally reaching a point in which the patient could no longer navigate through his own house, other than by trial and error. The condition eventually evolved into a case of Alzheimer’s disease. The authors suggest that topographical disorientation can result from neurodegenerative processes in brain structures and therefore can be progressive.

Brunsdon et al. (2007) [19] present the case of a six year old infant with topographical disorientation named CA in the study. CA was trained in route finding and recognition of landmarks and buildings in his school. The authors noticed that although CA presented severe impairments in spatial learning and topographical skills, and moderate visual agnosia (difficulty recognizing familiar landmarks or objects), CA was able to follow verbal cues consisting of few steps between familiar landmarks (i.e. go to the red wall and then downstairs). However, he was unable to follow directional verbal instructions (i.e. turn left and walk two steps). The treatment for CA was designed in several steps to allow measurement of treatment effects independent of spontaneous recovery or other developmental factors. Four variables were measured during route-following tasks at school, namely, the percentage of routes failed, the percentage of steps failed (intermediate steps to reach the final destination), total number of hesitations (stopping in confusion for more than 2 seconds), and the total time taken to reach the desired destination. A set of routes at CA's school was defined. CA received training for half of these routes and no training for the remaining routes (control condition). CA showed improvement in route navigation (in terms of the four wayfinding metrics identified above) for the group of routes for which he was trained, but not for the routes in the control condition. These results suggest beneficial effects of the reported treatment in the rehabilitation of topographical disorientation in the pediatric population.

Antonakos (2004) [8] conducted a study on the compensatory techniques used by people with topographical disorientation in daily life situations. The rationale was that these compensatory strategies might be incorporated into a suitable treatment for TD. Antonakos emphasized the importance of real world wayfinding tests over tests of abstract spatial abilities, which do not yield information about compensatory techniques. The author selected three individuals who experienced navigational difficulties in familiar environments due to visuo-spatial impairments. The individuals included in the study could navigate independently and communicate clearly. The author visited the individuals at home, and had them to complete a set of structured tasks, the first being a navigation task. Participants were asked to navigate inside their homes, while the examiner followed closely, taking notes of navigational strategies. The second task was an object location task. The examiner affixed a piece of red paper at eye level in a room. Participants were asked to locate this piece of paper. The examiner subsequently questioned the participants about the strategies deployed. The third task was a mapping task. The examiner had the participants describe what they saw when they imagined coming home through the front door. The fourth task was a recall task about places frequented outside of the home. Participants listed places they could visit independently, and the strategies used to find these places and navigate within them. Participants were also asked about the usefulness of maps and their map-drawing abilities.

Based on the above test battery, the author observed differences in the severity of topographical disorientation among participants. Consequently, individual wayfinding strategies varied, consisting of different combinations of landmark detection, visual scanning, landmark sequencing, and body position reconfiguration. The author concluded that: navigational independence and the severity of topographical disorientation is case-dependent; compensatory strategies of choice vary according to individual capacity and needs; and, visual scanning and the use of landmarks seem to be strategies of choice. Antonakos recommended further studies, in order to develop means to support independent navigation for people with topographical disorientation.

Stracciari et al. (2002) [161] studied twelve patients with isolated cases of temporary topographical amnesia (TTA). Temporary topographical amnesia refers to the temporary inability to recall the route or spatial relationships among elements in the environment, while retaining the capability of recognizing the individual elements themselves. These patients did not present any signs of neurological deterioration. The authors performed cognitive evaluations several months after the last observed episode of TTA . A group of twelve patients of the same age range with no reported topographical disorientation served as a control group. Six months after the TTA episode, both the TTA and control groups completed a series of tests designed to detect neurological damage or dementia. Neither group exhibited pathological issues. However, on the "Map of Italy" test, an assessment of orientation abilities based on survey spatial knowledge, significant differences between the control and TTA group were found (P ¡ 0.003). The authors concluded that isolated episodes of TTA are not necessarily associated with, or serve as predictors of, neurological damage, and that further research is required using larger samples and longer follow-up times.

Davis & Coltheart (1999) [33] present a case study of a 46 year old woman with topographical disorientation concomitant with memory, spatial perception and cognition issues. The authors refer to the patient as KL. KL suffered a brief episode of left-sided hemiparesis during a severe migraine headache. Three years later KL was referred to the practitioner, reporting memory problems and a tendency of becoming lost, along with symptoms of topographical disorientation. KL reported a poor sense of direction, difficulty retaining street names and relating them to a position in the town and difficulty learning new routes when she moved to a new hometown. KL compensated for these deficits by using a landmark-based route-learning strategy. She was aided by her daughters, who made a sequential list of landmarks between two places that KL visited often (i.e. her home and the grocery store). The authors applied a series of tests to assess both general perceptual and cognitive processes and specific topographical abilities. It was found that KL presented impairments in the acquisition of new verbal knowledge and diminished verbal intelligence when compared to performance intelligence. She presented a severe impairment in a mental rotation of personal space (route following) test. KL tended to become confused while following a map if she was not allowed to rotate the map or rotate herself towards a cardinal point.

The authors designed a compensatory strategy based on mnemonics tied to the sequence of names of the streets in KL's hometown. Such mnemonics were learned in sentences in the order of appearance of the streets, starting at KL's point of entrance to downtown. KL was asked to drive along the streets selected, taking note of the landmarks identified in a map. KL's performance in street finding was assessed prior to the above intervention, after each training session, and two months after the last training session. KL showed statistically significant changes from baseline in street name recall, street location recall, and landmark knowledge tasks after the third training session, and in the 2 month post-intervention tests. Although the authors designed a treatment that could be generalized, KL reported in the post-treatment evaluation that she had learned to drive to a friend's house in an unfamiliar part of town. KL accomplished this by following the pre-intervention technique (learning a linear sequence of visual landmarks). Therefore, KL did not exhibit a generalization of the acquired technique to navigate new environments. The authors concluded that: the treatment of topographical disorientation should be adapted to each patient's condition; and, further research towards the development of efficient strategies for the rehabilitation of topographical orientation is required.

### 1.3.4 Conclusion

The reviewed literature indicates a need for further investigation in the rehabilitation of topographical disorientation and compensatory techniques for it, particularly in the development of wayfinding strategies or tools. Our survey of the last eight years of research in the field confirm that there is indeed a paucity of literature on the rehabilitation and treatment of topographical disorientation, and that research towards establishing clinical standards of practice and technology to facilitate topographical orientation are required.

## 1.4 Objectives

In light of the above review, the main objectives of this thesis are:

A) To investigate methods of realizing a context-aware, wearable mediated environment system for indoor navigation, and

B) To investigate standard methods of quantifying the benefit provided by such a system during indoor navigation tasks.

Stemming from the first primary goal, there are several secondary objectives, namely:

A1) To develop a navigation algorithm, based on a spatial map of an indoor test area, and an identified set of geographical decision points, to efficiently ”route” the user from a given location to the target destination;

A2) To synthesize a context-aware wearable device capable of providing a mediated reality experience;

A3) To investigate the preferred graphical navigational tools for a mediated reality guidance system, considering the form of spatial knowledge (landmark, route or survey), graphical presentation (compass, text, icon, top/side view) reference frames (egocentric or allocentric); and

A4) To ascertain the impact of mediated reality location-aware navigational tools on human wayfinding performance.

## 1.5 Roadmap

The roadmap for this thesis is based on the above objectives. Each chapter of the thesis is structured as an independent journal article.

**Chapter 2** We present an extensive literature review of indoor localization technologies. We make recommendations about the creation of context-aware systems that can be used to enhance the user's topographical orientation skills.

**Chapter 3** We propose an automatic routing engine that effectively reduces the navigational effort required to negotiate a simulated environment. The routing engine accounts for the physical abilities of the patient, environmental barriers and dynamic building changes.

**Chapter 4** We propose four different graphical indoor navigational tools designed using different combinations of spatial knowledge (landmark, route or survey), graphical presentation (compass, text, icon, top/side view) and reference frames (egocentric or allocentric). We evaluate user preference for these tools and introduce a novel wayfinding metric based on a relative energy expenditure ratio. Each tool is evaluated objectively and subjectively.

**Chapter 5** We introduce a Mediated Reality Localization Aware (MERLA) system that offers wayfinding tools for human indoor navigation. We asses the system's impact on indoor topographical orientation skills using two of the navigational tools proposed in chapter 4, presented via the MERLA system. Collectively, objective and subjective data with 6 subjects reveal a strong user preference for navigation with tools over navigation without tools.

**Chapter 6** We present a summary of the scientific contributions of this thesis.

# Chapter 2

# A review of indoor localization technologies

Torres-Solis J and Chau T. (Accepted in preliminary form for publication in Ambient Intelligence, ISBN 978-953-7619-X-X). *A review of indoor localization technologies: towards navigational assistance for topographical disorientation.* Book chapter. Ambient Intelligence (A. Lazinica, editor), In-Tech Publishers.

## 2.1 Abstract

Indoor localization technologies hold promise for many ambient intelligence applications, including in-situ navigational assistance for individuals with wayfinding difficulties. Given that the literature on indoor localization is vast and spans many different disciplines, we conducted a comprehensive review of the dominant technologies. We propose a taxonomy of localization technologies on the basis of the measured physical quantity. In particular, we identified, radio frequency, photonic, sonic and inertial localization technologies as leading solutions in the field. For each selected technology, the fundamental scientific mechanisms for localization are explained, key recent literature appraised and the merits and limitations are discussed. Recommendations are made regarding the

creation of context-aware systems that can be used to enhance a user's topographical orientation skills.

## 2.2 Introduction

Topographical Disorientation (TD) refers to a family of deficits in environmental orientation and navigation. Aguirre and D'Esposito [3] provide a well-accepted taxonomy of TD, arguing that difficulties in wayfinding may arise as a result of the combination of different cognitive impairments. For example, it is well recognized that TD and spatial navigation deficits are common sequelae of brain injury [179, 156]. Individuals living with post-traumatic effects of brain injury are oftentimes faced with symptoms such as weak visual scanning skills, or deficits in complex attention, prospective memory or sequential processing [90]. These symptoms cause problems of interaction with and perception of the surrounding environment even several years post-injury [36, 145]. It has also been argued that deficits in topographical orientation can lead to spatial anxiety or wandering behaviours [19, 161, 179].

It has been suggested that wearable navigation technologies such as Global Positioning System (GPS) can be a useful wayfinding tool for individuals with cognitive impairments [7]. However, GPS signals have limited coverage indoors (e.g., [69, 79, 63, 128, 198, 74]). Given that patients spend significant periods of time indoors - be it in acute and tertiary care hospitals or, subsequent to rehabilitation, at home, schools, office buildings, shopping malls, long-term care facilities - identification of potential technologies for indoor navigational assistance is imperative. An initial survey of the literature has suggested that a diverse collection of candidate indoor localization technologies exists across many different disciplines. This diversity makes it difficult to grasp the potential of an existing technology for the rehabilitation of individuals with topographical disorientation.

Localization technologies are critical to emerging location-aware guidance systems and support services for individuals who have wayfinding difficulties due for example to low vision [141], stroke [178] and traumatic brain injury [6]. In particular, regarding indoor navigation systems for individuals with topographical disorientation, localization has often been human-mediated rather than automatic. For instance, Liu et al. evaluated the benefits of navigational tools in real indoor environments [88]. However, the location tracking and tool display decisions in their experiments were not automatic, but controlled by the experimenters. In similar vein, Sohlberg et al. [159] found that individuals with wayfinding difficulties secondary to brain injury responded well to speech-based auditory directions from a wrist-worn PDA navigation system. However, like Liu et al., the PDA's navigational instructions were transmitted by a human operator at a mobile computer. Undoubtedly, there is immense opportunity to explore the potential of automatic patient indoor localization technologies in the emerging fields of cognitive prosthetics and situated assistive technologies. As a consequence, the overarching goal of this review is to systematically organize the literature on indoor human tracking technologies, and to ascertain their feasibility for eventual use in the realm of TD rehabilitation.

## 2.3 Literature selection

We combed the literature for candidate localization technologies that could serve to create an assistive device for individuals with TD in indoor environments. In particular, peer-reviewed journal articles published in English between 2003 and 2009, inclusive, were sought from three different academic databases, namely: Compendex, Inspec and Geobase, using the keywords, *"indoor location"*, *"indoor localization"*, *"indoor tracking"* and *"indoor positioning"*. After removing duplicate records, we arrived at 214 articles. To identify potential technologies applicable to the creation of a navigational assistance device that for individuals with topographical disorientation that offered accurate information in real time, the returned articles were subsequently screened according to the following inclusion criteria:

1. The article must focus on the development and experimental testing of a localization or navigation system: i.e., articles focusing on mathematical processing of localization data, or localization experiments in simulated environments were discarded.

2. The reported technology must:

    (a) be usable indoors, within a building or a larger space, i.e., technologies used to track a capsule inside the human body, or a device within a single room were excluded;

    (b) offer a localization accuracy of a mobile target within a 10 meter radius with a delay of 5 seconds or less;

    (c) be applicable to humans, i.e., systems designed for vehicles, large objects, or objects that relied on a fixed pose or odometry measurements of a robot were excluded; and

    (d) track and identify multiple humans concurrently.

Fifty three articles met such initial criteria. Such articles were subsequently scanned for alternate localization technologies that were referenced three or more times and that were not selected in the initial search. Eleven additional articles were included in this manner, totaling sixty four articles for consideration in the present review.

### 2.3.1 Taxonomy of localization technologies

The location of an object in space is determined by measuring a physical quantity that changes proportionally with the position of the object of interest. The present review is structured in terms of the measured physical quantity. The selected articles were divided

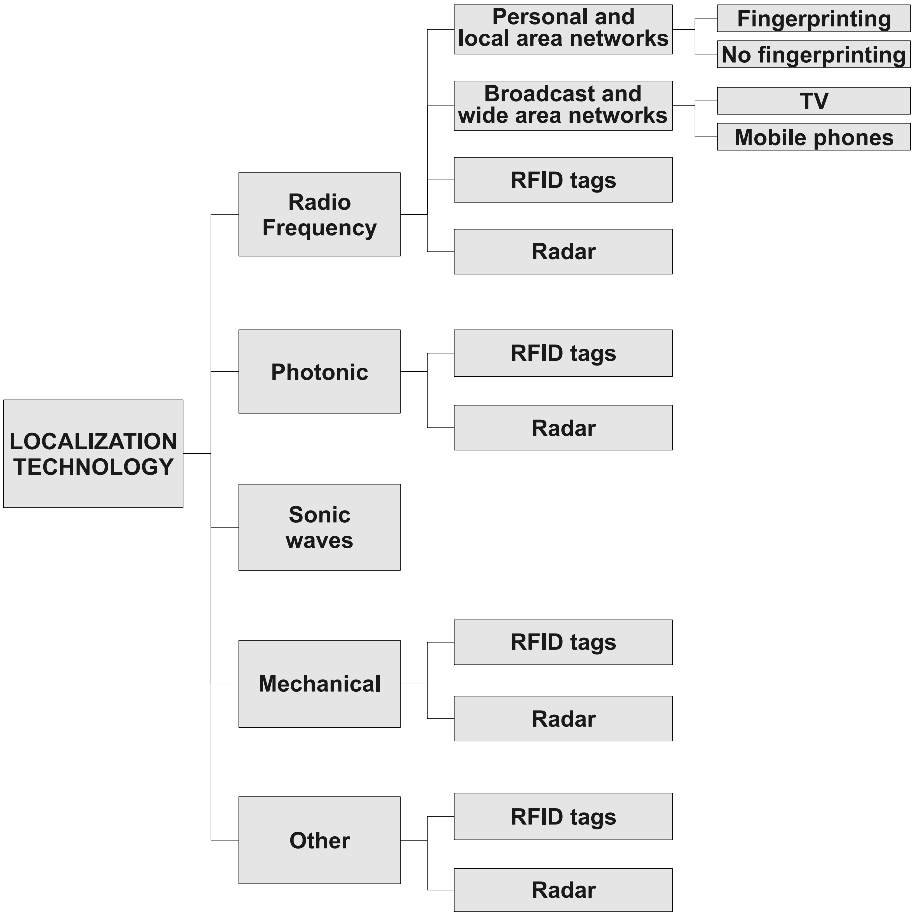

Figure 2.1: Taxonomy of indoor localization technologies by measured physical quantity and hardware technology

into six main categories based on the physical quantity measured, namely, (1) radio frequency waves, (2) photonic energy, (3) sonic waves, (4) mechanical energy (inertial or contact), (5) magnetic fields, and (6) atmospheric pressure. Each physical quantity grouping can be further subdivided according to the underlying hardware technology. Figure 2.1 summarizes this two-tiered taxonomy. Note that the latter two phenomena (magnetic and atmospheric) have been collapsed into one category, named, “Other” due to low article counts in these areas.

Where appropriate, articles are further differentiated by principal localization technique. For this third level of classification, the following localization technique definitions are provided, expanding on those proposed by Hightower and Borriello [62]:

**Triangulation** is a family of methods that include lateration, angulation and variations thereof. Lateration refers to the calculation of the position of the human subject based on his relative distance to several previously-known fixed points in space. Such distances are commonly obtained indirectly by measuring parameters that are proportional to distance. Time of flight and power attenuation of a radio signal are common indirect distance metrics [43]. Angulation refers to the calculation of the position of the subject using the angles of arrival of signals emitted from fixed points in space. [181, 166].

**Proximity** refers to a class of methods which establish the presence of the human subject in the vicinity of a sensor, which alone has limited sensing range and analysis capabilities. The proximity of the subject can be detected through physical contact, presentation of a device such as a magnetic band to an appropriate reader or through the monitoring of a physical quantity in the vicinity of the sensor, for instance, a magnetic field.

**Scene analysis** involves the monitoring of a wide area around the subject of interest from a specific vantage point. The commonly deployed sensors have broad coverage area and range. Examples include ceiling-mounted video cameras or passive infrared (PIR) sensors.

**Dead reckoning** refers to the usage of sensors that provide location updates, calculated using information about a previously-estimated location. Position estimation is commonly based on accelerometry and gyroscopy.

The ensuing review of literature will adhere closely to the taxonomy depicted in Figure 2.1. For each physical phenomenon, we will briefly present the general principles of localization, review articles in the relevant subcategories and comment on their relative merits and limitations. We will conclude the article with recommendations of indoor localization technologies suitable for addressing the development of assistive devices for individuals with TD.

## 2.4 Radio Frequency

An electromagnetic wave is the energy generated by an an oscillating, electrically charged particle in space. The generation of electromagnetic waves is known as a radio frequency emission.

Solutions in this category estimate the location of a mobile target in the environment by measuring one or more properties of an electromagnetic wave radiated by a transmitter and received by a mobile station. These properties typically depend on the distance traveled by the signal and the characteristics of the surrounding environment.

As depicted in Figure 2.2, most of the articles in this survey describe a Radio Frequency (RF) localization system. These articles can be further subcategorized according to the underlying hardware technology as listed below.

1. Personal and local area networks, including technologies such as IEEE 802.11, Ultra-Wideband (UWB), ZigBee, or Bluetooth, either as the sole localization technology [21, 191, 39, 84, 43, 131, 138, 83, 81, 114, 164, 60, 48, 195, 40, 139, 4, 194, 181, 49, 174, 12, 122] or as a contributing technology within a hybrid solution [197, 22, 199, 106, 127, 2].

2. Broadcast and wide area networks, including networks designed for localization purposes, such as the GPS and the Global Navigation Satellite System (GNSS) [139], and broadcast networks not originally intended for localization purposes, such as cellular phone networks [154, 55] and television broadcast signals [129, 130].

3. Radio-frequency Identification (RFID) tags [87, 68, 167]

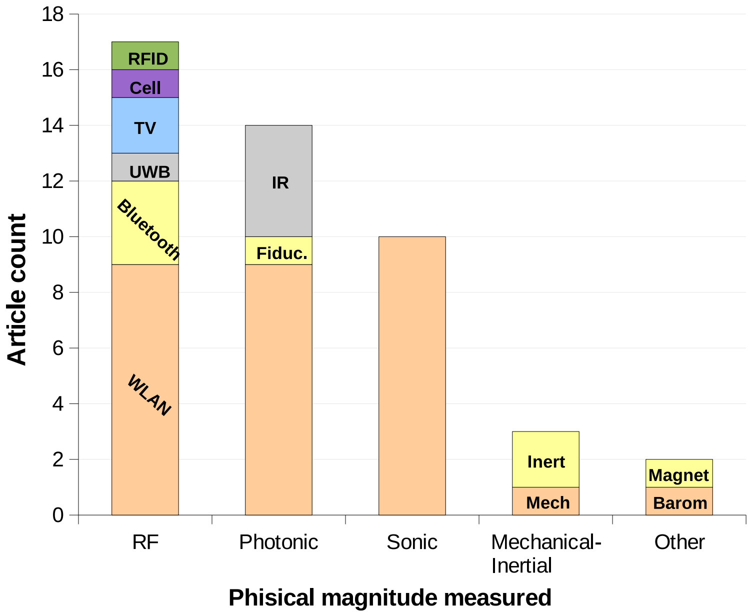

Figure 2.2: Distribution of articles by physical quantity measured

4. Radar [132, 144]

Each flavour of RF localization is reviewed below.

## 2.4.1 Personal and local area network-based solutions

### Fingerprinting-based localization solutions

Most articles included in this section propose the localization of mobile targets using a two stage process [197, 39, 131, 138, 83, 114, 12, 122, 191, 84, 164, 48, 195, 40, 139, 4, 194, 174]. The first stage consists of an off-line radio scene analysis (i.e., performed prior to localization) in which a mobile station extracts radio fingerprints, i.e., features from one or more metrics of the radio signal measured at predefined points in the environment. These radio fingerprints are proportional to the distance between the mobile receiver and the emitting station. Common metrics include the direction or angle of arrival (AoA), Received Signal Strength (RSS), or time of flight (ToF) of the incoming radio signal [110]. A radio map or database of fingerprints is created, storing signal feature values at each location along with the corresponding spatial coordinates. Some authors propose automated or assisted radio map creation techniques, exploiting the characteristics of the environment, such as the spatial configuration and the material composition of the environment [164, 67, 197].

The on-line stage comprises the active localization process where the mobile receiver extracts a fingerprint of the radio signal at an unknown location. Localization is commonly achieved by proximity techniques, i.e., finding the closest match between the features of the received radio signal and those stored in the radio map [197, 39, 131, 138, 83, 48, 40, 139, 4, 122, 191]. More accurate localization can be achieved using a triangulation-like process, in which several candidate locations (each with a fingerprint bearing some resemblance to that of the received signal) are geometrically combined to provide an estimate of the receiver location in space [84, 114, 164, 139, 194, 174, 12]. Algorithms deployed in the selection of the closest match or matches from the radio map include: 1) nearest neighbours techniques and variations thereof [39, 194, 12]; 2) Bayesian statistical matching [197, 191, 84, 131, 138, 139, 174, 122]; 3) maximum likelihood estimation [164, 48]; 4) correlation discriminant kernel selection [83, 114]; and neural networks [40, 4].

Some fingerprinting techniques also provide coarse estimates of orientation, for example, 4 different orientations [191, 12]. The radio map is created with a user transporting the mobile device. At a given location, a fingerprint is recorded at each possible orientation. Since the human body affects the propagation of radio signals, the fingerprint generated for each orientation will be different [191, 12].

Fingerprinting localization accuracy is commonly down to a few meters (i.e. within 3 metres 90% of the time [83] and within 3 metres 91.6% of the time [114]). The lowest number of base stations used to create the feature space of a fingerprint was one [197]. In other words, fingerprinting seems to provide reasonable localization accuracies without excessive hardware requirements. The most pressing challenge however is the non-stationarity of the radio map. This is reflected as differences in the measured signals during the on-line and off-line phases at the same exact location. The time-variant nature of the radio map can be attributed to radio signal propagation effects induced by dynamic aspects of the environment such as the presence or absence of people, elevators, moving doors and other environmental changes [87, 83, 12].

As a particular case, in [139], the authors proposed an indoor and outdoor hybrid localization system, combining GPS and WLAN localization technologies. The authors proposed handing off the localization responsibility between GPS and WLAN depending on their availability. Fingerprinting was done through a GPS-on-line stage, collecting positional information of the access points within a nearby building and geo-referencing these measurements with the information obtained through GPS. After this fingerprinting process, indoor WLAN positioning was achieved by estimating a point located among a set of the most probable locations. These locations were predefined by the user - i.e. copy room, cafeteria. The histogram of the RSS measurements was used to determine the location that best matched the histogram received. If the histogram did not closely match any known locations, a centroid algorithm estimated the location of the user from the locations of previously geo-referenced access points and probable nearby locations. The place detection algorithm, which relied on an almost perfect fingerprint match, yielded room level localization accuracy, while the WLAN localization algorithm, using the centroid of several probable locations, yielded an accuracy of approximately 30 metres.

### Non-fingerprinting-based solutions

RF-based localization can also be achieved without *a priori* analysis of the radio properties of the environment (i.e., without development of a radio map). Four of these articles, all of them based on UWB radio signals, rely on signal triangulation as the sole localization technique [60, 181, 49, 81], while in [43] localization is achieved by proximity and scene analysis.

Indoor localization based on triangulation of radio waves is a non-trivial problem because the transmitted signal can suffer obstructions and reflections. As a consequence, Non-Line-of-sight (NLOS) conditions emerge. In the presence of NLOS conditions, the radio signal can travel to the receiver through a non-direct path, giving rise to erroneous distance estimates.

To overcome these problems, the use of UWB radio signals has become the most novel solution in radio frequency-based solutions. The properties of ultra-wide band, short duration pulses mitigate the propagation problems associated with multi-path radio propagation. The most representative example is the system proposed by Venkatesh and Buehrer. They introduced a triangulation localization system based on impulse UWB radio signals [181]. They suggested that the statistical parameters describing the distribution of the received root-mean-square delay spread (RDS) serve as the best discriminant estimator between Line-of-sight (LOS) and NLOS signal propagation. This means that the statistical parameters defining the RDS of the received signal can be compared against a predefined rule set to determine if the signal was received via a direct or indirect path. Subsequently Venkatesh and Buehrer tracked a mobile station though 71 predefined locations within a building, achieving localization accuracies ranging from 1 centimetre to 2 metres. As another example of RF triangulation-based schemes, Krejcar and Cernohorsky presented a localization system [81] that relied on the triangulation of RSS metrics. Room-granularity accuracies were reported but further details of the triangulation or localization schemes were not revealed.

Finally, a system based on a combination of scene analysis and proximity techniques using a Bluetooth ad-hoc network was presented in [43]. Bluetooth inquiry signals were used for localization. In inquiry mode, a bluetooth device inquires about neighbouring bluetooth stations. This inquiry process consists of scanning for devices in the vicinity, using a sequence of different power levels. Low power levels will detect devices in close proximity while high power levels will include devices that are located farther away, providing coarse distance estimates in this fashion. This approach requires a fixed or "anchor" node which establishes the position of nearby mobile nodes. Subsequently, the localized nodes can establish the position of other undetected mobiles nodes in their vicinity, creating an ad-hoc localization network. The reported localization error was 1.88 meters.

## 2.4.2 Broadcast and wide area network solutions

### Solutions based on television signals and cellular networks

The solutions in this section are based on RF infrastructure transmitters that cover a wide area, and while not originally designed for localization, can be adapted to provide indoor localization services. In particular, two such technologies were identified: television (TV) broadcast signals [129, 130] and cellular phone networks [154].

Rabinowitz and Spilker [129, 130] proposed the use of synchronization signals already present in the Advanced Television Signal Committee (ATSC) standard for compliant digital TV signals. As the signal properties and geometrical arrangement of the TV broadcast network have been designed to penetrate indoors, they offer significantly greater indoor coverage than GPS-based solutions. Implementation of a localization solution would require no modification of the existing broadcast signal. To overcome the inherent lack of synchrony between stations due to clock imperfections, Rabinowitz and Spilker deployed a fixed reference station that transmitted an offset correction signal. A mobile station then calculated the ToF of the signal, and subsequently the distance to each TV broadcast station. As the positions of the broadcast stations were fixed and known, the position of a mobile receiver could be estimated. At least three visible transmitting stations were required for triangulation purposes. Rabinowitz and Spilker presented experiments in indoor environments in which they obtained a mean localization error ranging from 10 to 23 meters depending on the environment.

Hu et al. developed a method for the localization of mobile phones inside a cell [154] using fingerprinting techniques. Invoking a method for the automated creation of a radio fingerprint of the cellular signal, Hu et al. argued that granular localization can be achieved in indoor environments by statistically matching the fingerprint of the received signal with a record in the radio map. The authors emphasized that the localization accuracy in this case is highly dependent on the size of the cell and the characteristics of the environment. This localization solution can be considered a combination of scene analysis (the off-line phase) and proximity techniques. Unfortunately, the improvement achieved in localization accuracy over conventional cell-ID localization was not reported.

### 2.4.3 Solutions based on RFID tags

An RFID system is commonly composed of one or more reading devices that can wirelessly obtain the ID of tags present in the environment. The reader transmits a RF signal. The tags present in the environment reflect the signal, modulating it by adding a unique identification code [87, 124]. The tags can be active, i.e., powered by a battery, or passive, drawing energy from the incoming radio signal. The detection range of passive tags is therefore more limited.

Lionel et al. [87] proposed a localization system named LANDMARC, using active tags. Reference tags were located in known, fixed positions in the environment. The reader was also situated in a fixed position. To locate a mobile tag, the reader scanned through 8 different power levels for tags in the vicinity. When a mobile tag was detected, the receiver compared the power returned by the reference tags and the mobile tag, determining the closest reference tags using a nearest neighbour algorithm. The position of the mobile tag was determined by triangulating the position of the nearest reference tags. The authors reported a localization accuracy of 2 meters, 75% of the time. The maximum localization delay was of 7.5 seconds.

Jia et al. [68] proposed a hybrid radio and vision based system which used RFID tags and a stereo camera for robot navigation purposes. To estimate the location of the mobile unit, RFID tags were used to mark walls and obstacles within the environment. The RFID detector comprised of a directional antenna, which yielded the general direction of the RFID tags detected. When a tag was in proximity of the robot, it obtained images from the stereo camera to estimate the distance to the obstacle marked by the RFID tag. Subsequently, the ID of the tag was compared against entries in a tag location database to determine if it belonged to a fixed landmark (i.e. RFID tag fixed to the wall) or an obstacle prone to change its position in the environment (i.e. a chair or a human). If the tag belonged to a fixed object or location, the information from the camera, combined with the directional orientation obtained from the RFID tag, were used to estimate the distance and orientation of the robot with respect to the tag. The localization accuracy was of 8.5 centimetres. Although this localization system was designed for a robot, the constraints on the robot's movement and posture were minimal. Therefore, this system might be adapted to human localization, at the risk of accuracy reduction.

Finally, in [167], Tesoreiro et al. introduced a localization system based on proximity to RFID tags. In this system a museum visitor used a personal digital assistant (PDA), which served as an automated museum guide. To estimate the position of the user, the PDA obtained the ID of RFID tags in the vicinity. Each tag was associated with an exhibit in the museum. The ID of the detected tag was subsequently transmitted to a server, which returned information about the exhibit in proximity to the user. This information was displayed in the PDA screen. The localization accuracy of this system was not reported. However, the accuracy was related to the density of tags in the environment.

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### 2.4.4 Solutions based on a radio frequency radar

Roehr et al. [144] presented an extension to the conventional frequency-modulated continuous-wave radar. The particular characteristic of this system was that it used two-way radio communication. Both fixed and mobile units were capable of transmitting and receiving a frequency modulated signal with a 5.8 GHz carrier. The fixed and mobile clocks were synchronized before distance and velocity estimations could be calculated. Once the units were synchronized, the fixed unit emitted a signal, which arrived at the mobile station. Subsequently, the mobile station sent a reply to the fixed station, which was synchronized using the signal just received from the fixed station. The round trip time of the signal was used to calculate the distance between the fixed and the mobile stations, while the frequency deviation was used to estimate the velocity of the mobile unit. The experimental setup included one experiment within an office building, where distances ranging from 5 to 25 metres were measured with the radar system. These distance measurements were then compared against the measurements obtained with a laser range finder. This experiment was designed to test line-of-sight conditions only and yielded measurements with a deviation of less than 3 centimetres when compared to laser range finder measurements.

In [132], the authors presented a radar indoor human tracking system, which exploited the Doppler effect of moving objects and micro-Doppler signal features that are particular to human movements. Various movements of the human body were classified based on the Doppler features received by the radar system. Such features were obtained from a joint time-frequency analysis, using the short-time Fourier transform and the reassigned joint timefrequency transform. The authors also proposed a scheme for tracking several human beings concurrently; the Doppler separation effect between moving humans was exploited, while target differentiation was realized using an antenna array that formed directed beams. Three antennas and two frequencies were required for multiple target tracking. Finally, the authors presented experiments to determine the range of the target, using frequency diversity, and studied the effects and errors introduced by the attenuation due to walls in the environment. The authors concluded that the properties of human movements can be exploited for localization purposes and that human localization using radar technologies is challenging within an indoor environment. They suggested a few techniques that might improve indoor localization, such as the placement of the radar as far away from the walls as possible.

### 2.4.5 Limitations

The propagation of RF signals in indoor environments poses a central challenge. Certain materials within the indoor environment affect the propagation of radio waves. For example materials such as wood or concrete attenuate RF signals, while materials such as metals or water cause reflections, scattering and diffraction of radio waves. These effects lead to multipath radio wave propagation, which encumbers accurate calculation of the distance between the transmitter and the receiver [181, 186, 154, 83, 198, 164, 144, 110]. Several authors have proposed techniques to compensate for these inaccuracies by automatically generating radio maps which consider the structure of the building [164, 154, 67]. However, a comprehensive model of all the materials in a complex environment such as a health care facility or a patient's home is a non-trivial problem.

The propagation of radio waves are adversely affected by changes to the physical environment such as the rearrangement of furniture, structural modifications or movement of personnel within a building. Clinical setting are under constant change; elevators, personnel and large metallic structures such as beds and wheelchairs are constantly moving through the building. In these environments, the radio properties are highly dynamic, and a radio map captured at a certain point in time cannot be used reliably for localization without accounting for these dynamic changes [87, 84, 191, 12].

Interference and noise are often-mentioned challenges [83, 175]. Although some solutions operate within a reserved radio band [129, 154, 130], most of the research is conducted on open spectrum bands. This means that these solutions must account for the increased risk of interference due to other systems sharing the same frequency bands of the radio spectrum [84].

Finally, the usage of radio transmitting devices is often times restricted in critical areas of most healthcare facilities, according to recommendations made by the Association for the Advancement of Medical Instrumentation (AAMI) [1] and other standards or regulatory bodies. These restrictions limit the deployment of localization systems based on non-broadcast radio waves to specific, non-patient care areas, e.g, waiting rooms.

Localization technologies based on RF technologies can be attractive due to the ubiquity of certain infrastructural technologies, such as wireless data networks, that may already be present in the facilities. Care must be taken, however, in evaluating the impact of the physical environment on the RF localization technologies, as the solution may be rendered non-operative in certain clinical settings.

## 2.5 Photonic energy

Light refers to the phenomena of electromagnetic radiation at wavelengths within the visible range, which extends approximately between 380 and 750 nanometres. Photonic energy refers to the energy carried by electromagnetic radiation in this wavelength range, known as visible light, or in its lower or upper vicinity, known as ultraviolet and infrared light, respectively. A photon is the minimum possible discrete amount of light energy.

Solutions in this category rely on the photonic energy received from infrared or visible light emissions or reflections, to estimate the position of an object in space.

The articles selected for this section can be distinguished based on the sensor required to estimate the location of the tracked object. Some articles proposed the use of cameras to locate a mobile subject or device via image processing [123, 5, 193, 52, 46, 192, 196, 184, 76, 143, 64, 105, 18]. In contrast, some other articles present localization solutions based on non-image processing devices [28, 121, 120, 24, 66, 185].

Methods based on image analysis are all of the scene analysis persuasion. The classical model of computer vision-based location detection consists of 4 main stages [5]

1. Image acquisition, normally through a video camera
2. Segmentation of the image and extraction of relevant features
3. Selection of the closest match or matches of the detected features against the entries of a database of features (e.g. edges or fiducials). This process typically involves mathematical transformations of the spatial relationships between the features detected to account for the variability in scale, rotation or luminance of a given scene.
4. Computation of the pose of the camera. This consists of estimating the position and orientation of the camera that could have given rise to the observed image, assumed to be a distorted and rotated version of a database image. The selection of the closest match is achieved as in the previous step.

We can subsequently distinguish between localization systems that rely on image processing that exploits natural environmental features and systems that rely on the detection of a predefined synthetic pattern (i.e. fiducial) in the environment.

Consequently, the articles included in this section were organized in three main groups: 1) image processing and natural feature extraction, 2)image processing and fiducial recognition, and 3) non-image processing sensors. This organization is presented in the following sections.

### 2.5.1 Image analysis, natural feature extraction and recognition

Natural feature extraction refers to the mathematical processing of an image to extract a set of numerical values that uniquely represent that image. Features of an image are commonly selected from its colour histogram [46] or from structural edges and their spatial relationships [5]. A reduced subset of these features is subsequently defined to uniquely identify the image.

### Mobile camera systems

Articles grouped in this section consider solutions where the camera was carried along by the subject or device being located. In most cases the localization process involves two stages, analogous to the two-stage fingerprinting process described for wireless localization solutions. In the off-line stage, images of the environment are captured at predefined locations. Each image is processed to extract its unique features. Subsequently, the extracted features are stored in a database along with the associated camera position and orientation, at which the image was captured.

In the on-line stage, the camera captures an image, and image features are subsequently extracted. These features are compared to the entries in the feature database, either directly (to define a crude location of the camera), or through spatial transformations that yield the best match between the features in question and those in the database (to obtain more accurate location estimates). Such transformations reflect the differences in between on-line and off-line image capture locations. Once the best matching set of database features is identified, the corresponding database entry for camera position and orientation is used to estimate the absolute location of the camera.

Articles adopting a mobile camera system include [5, 193, 52, 46, 192, 143, 64]. It must be noted, however, that these articles propose the indoor localization of robots. Nevertheless, the algorithms used in such articles are not strictly dependent on properties of the robots and can be easily adapted to human localization. Three distinctive examples are presented in this section.

Observing the rectilinearity of human-made indoor environments, Aider, Hoppenot and Colle [5] proposed a localization system based on a mobile monocular vision system which exploited straight line environmental features. The maximum localization error reported during their experiments was 20 centimetres, and the maximum angle estimation error reported was 2.5 degrees.

Frontoni and Zingaretti [46] used a single colour camera to detect coloured areas of an image and their spatial relationships, which were, in turn, used as features. Through a rotation invariant feature transformation, they estimated the most probable location of the camera from a previously created database of features. The authors reported indoor localization errors less than 50 centimetres, 94% of the time.

In [64] the authors presented a navigation system for a humanoid robot, which can be extended to the case of human walking. Location determination was accomplished in two stages. In the off-line stage, images were captured while following the route between two points. The on-line stage involved autonomous robot navigation between two arbitrary points while capturing images. To achieve localization, an algorithm correlated freshly captured images with images in the route database. In this way, the unprocessed raw image was considered as a large set of features. Correlation analysis yielded the position deviation between the learned route and the current position. Temporary occlusions were detected as sudden drops in the correlation. The maximum position deviation reported during an experimental 17 metre long route, was 0.9 metres. This represents a deviation of 5.3% of the walked distance.

### Fixed camera systems

When the camera or cameras of the system are mounted in fixed locations in the environment, the structural features of the building cannot serve as discriminant factors for localization purposes. Instead, features of the object being tracked must be used. In this way, if the salient features of the object or objects appear in the field of view of the camera, the location of the object or person can be calculated with respect to the camera's fixed position. The position of the object of interest in the environment is estimated based on its position within the captured image, and the spatial distribution of its salient features.

Although several candidate articles discussed solutions for tracking the position of a person using cameras fixed in the environment, few considered tracking a person in a building. Instead, most of the articles presented a solution in which the tracking process was limited to the field of view of a single camera. Therefore, only articles [123, 196, 184, 105, 18] were considered as an indoor tracking solution based on our inclusion and exclusion criteria.

In [123], the authors proposed a system that detected elements of the scene which were not part of the static environment. Through segmentation, the colour histograms of the region or regions of interest were obtained, along with a vertical colour average to estimate a general vertical orientation of the object detected. In this way, the algorithm accounted for the global colour scheme of the clothes of a person while standing up. A camera, located at the entrance of the test environment, was used to create an initial colour model of each person. Fifty subjects were tracked within an office environment using surveillance cameras in this fashion. Visual overlaps between cameras allowed constant tracking of subjects. The authors reported correct user recall values of 87.21% with an availability of 73.55%.

A similar approach was presented in [196]. The authors used colour-based features assuming vertical differentiation of colour regions of a human figure while standing up. To account for movement between cameras with no visual overlapping coverage, the authors proposed the creation of a connected graph that represented the areas covered by each camera. The edges of the graph denoted physical connections of the areas covered by the field of view of each camera. This connected graph was used in the probabilistic modeling of the movement pattern and traffic constraints of the user, to improve recognition and tracking accuracy.

Pursuing a slightly different approach, [184] proposed a distributed sensor network based on image processing. The robustness of the solution relied on overlapping the visual field of several cameras, and distributing computational processing for localization purposes among the elements of the distributed network. Features were extracted using a principal components analysis of features obtained by differencing consecutive segments of the image. The field of view overlap of different cameras allowed robustness against occlusions. The authors demonstrated the feasibility of human tracking in a crowded setting. The localization accuracy, however, was not reported.

In a similar vein, [105] proposed a system with 4 cameras with partially overlapping coverage areas. Colour and non-colour features were used to account for areas of interest in the image that yielded colour and illumination information, respectively. These cameras were calibrated to estimate the 3D position of the user within the 2D image using a projective algorithm. Using an evidential filter, particles represented the probability of a user being in a certain location. Experiments were conducted with multiple users navigating a room concurrently, without deliberately avoiding occlusions. Three hundred particles were used to represent each user. In some cases the users wore similar clothes. Some of these users walked out of the field of view of some of the cameras intermittently. The reported localization accuracy of a single user using the 4 cameras was 0.15 m, while using a minimum of 30 particles for the evidential filter.

Finally, the Easyliving project [18] proposed the usage of image-based localization systems to provide context awareness within intelligent environments. The project was based on ceiling-mounted stereo vision cameras capable of estimating the anatomical posture of humans or the orientation of objects in the environment. The identification of the subject being tracked was based on colour and structural features. The localization accuracy was not reported.

### 2.5.2 Image analysis, fiducial markers

Fiducial image detection differs from natural feature detection in that the image processing algorithms are designed to detect predefined, synthetically created, patterns in the environment. These patterns are called fiducial markers [109, 41].

In principle, localization algorithms based on fiducial recognition are very similar to localization based on natural feature recognition. However, as the properties of the image to be detected are constrained, there is no need for an *a priori* stage to extract the features of the fiducial. A database is still required to determine the location of the camera relative to a reference frame, fixed with respect to the environment. In this case, however, the database can be created automatically by storing a numeric ID associated with the fiducial along with its coordinates in the environment [193]. The ID of the fiducial can be encoded within the fiducial image, analogous to how the image of a bar code represents a numeric ID. Some reported advantages of fiducial recognition over natural feature recognition are reduction of computational requirements, improved detection accuracy and resilience to noise artifacts [109].

In [193], the authors proposed a position detection system for robot navigation in indoor environments. They conducted a simple experiment using a fiducial marker as reference. They presented an image analysis technique based on homography to obtain the relative position of the camera with respect to the fiducial marker. Although developed for a robot, the localization technique is not constrained to intrinsic properties of the robot, and can be applied to human localization.

Kim and Jun [76] introduced a wearable indoor localization system composed of a portable computer, a head mounted display and a camera. Localization was achieved through image processing, combining fiducial markers and natural visual feature extraction. Localization with fiducials was achieved through an open source library called ARToolkit [72]. The localization algorithm detected a synthetic visual pattern in the image captured by the camera. Using affine transformations, the authors estimated the distortion and scaling of the fiducial due to angle of view and capture distance. With this information, the exact position (i.e. distance and orientation) of the camera with respect to the marker could be determined. The authors modified ARToolkit, adding an adaptive illumination thresholding algorithm and an algorithm for natural scene feature recognition, which determined the location of the person when there were no fiducial markers in view. Natural feature recognition was achieved by analyzing the color and hue histograms for a sequence of frames. The authors defined a "location" as a sequence 64 consecutive frames. Hence, each location was defined by a high dimensional space, namely a sequence of 64 colour and 64 hue histograms. A Linear Discriminant Analysis (LDA) was applied to reduce the dimensionality of the features which defined each location. The first five LDA coefficients of each frame were used as descriptive features of that frame. The sequence of features in consecutive frames defined a location. An off-line navigation phase facilitated the creation of a database of natural features of the building. To estimate the location of the user, the vector of features obtained from the last 64 frames, defining the current location, were compared against the features in each entry of the database. The difference between a feature vector captured by the camera in the on-line stage against feature vectors stored in the database were quantified by the Euclidean distance. If the Euclidean distance was lower than an unspecified threshold, the location of the person was defined as the matching database coordinates. In this fashion, the system yielded the general location of the user in a continuous fashion. The exact location of the user was determined using fiducial markers in the field of view of the camera. The location information obtained by both visual systems was presented in a virtual map, along with instructions to complete a predefined path through the head mounted display. The localization accuracy of the system was not reported.

### 2.5.3 Other photonic sensors

Articles included in this section make use of non-image capturing Infrared (IR) sensors [28, 121, 120, 24, 66, 185].

In [28], the authors presented an IR proximity-based localization system, which provided museum visitors with useful information about exhibits in each hall. For this purpose, IR emitters were installed in the ceiling of the door frames of every room. Each emitter transmitted a unique ID using the Infrared Data Association (IrDA) protocol. The visitor carried a Personal Digital Assistant (PDA) with an infrared port. The PDA contained a database of visual and textual information of the exhibits, as well as maps of the museum. Upon reception of a new ID, the PDA automatically presented the map of the corresponding hall. While in the hall, a graphical user interface in the PDA helped the visitor to obtain information about a particular exhibit. The authors noted some problems while deploying this localization system, in particular, noise and reflections of IR signals. The user localization granularity of this system was down to the scale of a room.

A combination of scene-analysis and triangulation is presented in [121]. In this solution, a unique ID was modulated by the IR emitter. The carrier frequency used for modulation was changed in a cyclic way, from low to high frequencies. As the attenuation properties of an infrared signal are frequency-dependent, ID's modulated at lower frequencies can be successfully detected farther away from the emitter. However, the power of the IR signal decays in a nonlinear fashion with distance. To characterize this power decay, the authors obtained off-line measurements of the received signal in the vicinity of the emitter, in a similar fashion to fingerprinting for RF signals. The authors measured the ID detection success rate in 10 cm concentric regions, at steps of 5 degrees, repeating this process for different modulating frequencies. Instead of creating a database of the signal in each point, the authors modeled the decay of the signal with an equation that was dependent of the orientation of the receiver, the distance between receiver and emitter, and the modulation frequency. Using this approach the system achieved a maximum localization error of 10 centimetres, within an area of 5 square metres. Although a building-wide experiment was not conducted, the usage of a unique ID per transmitter would allow the deployment of multiple emitters in a cellular arrangement to cover large areas.

Petrellis et al. [120] presented a localization system consisting of two IR emitters fixed in the environment, and two receivers installed on a mobile unit. The transmitters were mounted facing each other on the walls of a corridor, while the receivers on the mobile unit faced away from each other. Each emitter transmitted a series of unique cyclic data patterns, modulated at a carrier frequency of 38 Hz. The opposite-facing arrangement of the receiving sensors facilitated detection of user orientation and, at the same time, discrimination between signals received via direct path and reflected signals. Reflection rejection was enhanced using a predictive model, which took into consideration the immediate previous location and orientation of the user. Since the system relied on predictions of future position and orientation of the mobile device, the estimation rules constrained the maximum linear and angular speeds at which the system was reliable. Given that the emitters transmitted unique sequences, the authors proposed a cellular-like spatial emitter arrangement to cover extensive areas. The system was sensitive to moving personnel and other objects that caused reflections although compensation algorithms reduced such effects. The localization accuracy was not reported.

Cheok and Li [24] presented a localization system which made use of existing fluorescent lamps in a building. A user carried a wearable computer instrumented with a photo-detector and a gyroscope. Each fluorescent lamp emitted an ID, associated with the location of the lamp. The ID was encoded through pulse frequency modulation. The encoded information did not introduce perceptible illumination effects. The photo-detector and gyroscope were mounted on a cap, worn by the user. The gyroscope served to obtain orientation information. The wearable computer was carried on a vest, worn by the user. The area illuminated by two lamps transmitting different location ID's could not overlap, since this would cause interference, resulting in the inability to detect the encoded signal. Whenever available, location information was presented to the user via the wearable computer. Such information was overlaid on the user's visual field through a Head Mounted Display (HMD). The reported localization accuracy was within three to four meters. Although this accuracy is dependent on the lamp and user heights, these numbers were not provided. The minimal separation between lamps was of 2.31 metres.

iGPS, commercialized by Metris (formerly ArcSecond) [66], is a triangulation-based localization system for tracking assets, personnel or any other mobile elements. To accurately estimate the position of a receiver, a pair of eye-safe IR laser emitters radiate a signal using two different wavelengths, while a an infrared strobe provides a reference signal. Using signals from 3 or more transmitters, the receiver calculates and transmits its position to a central data collecting station. In order to estimate the orientation of a solid body, two or more receivers are attached to it. The iGPS system claims to offer sub-centimetre accuracies.

Scientists from Olivetti Research designed the Active Badge location system, which consisted of small badges that transmitted a unique ID via IR emitters [185]. The badges were worn by people, who could then be located when in the vicinity of a receiving station. The badge transmitted a unique identification code every 10 seconds. The system offered sub-room accuracy, and was used to redirect phone calls for personnel.

### 2.5.4 Limitations

Common problems reported for photonic sensor localization are the ambient noise in the form of light or thermal radiation [5, 121, 196], signal reflections [28, 86, 121] and in the case of image processing solutions, illumination variability [123, 184, 162, 196].

In image processing solutions, ambient noise is usually overcome by image filtering techniques. In the case of IR sensing, effects of ambient noise can be mitigated by using a combination of different modulation frequencies [121, 66].

Another problem commonly mentioned in the surveyed articles is the occlusions caused by dynamic elements of the environment [5, 52, 46, 184, 18]. For instance, in the experiments performed in [121], the introduction of new objects or humans was specifically avoided during the experiments. In order to reduce the risk of visual occlusions by humans and objects, solutions comprising building-mounted equipment commonly install the detection equipment on the ceiling [28, 185]. Another way of reducing occlusion is to deploy sensors with overlapping coverage areas [123, 184, 66].

However, clinical settings and public indoor areas like shopping malls are oftentimes densely populated. Consequently, occlusion conditions can emerge frequently even with ceiling mounted sensors. Therefore, if a photonic-based system is to be considered for localization purposes, it may be advantageous to simultaneously invoke a secondary tracking system to assist in the localization process during periods of optical occlusion.

In the case of laser based-solutions, only class 1 laser devices should be used, which are classified as "eye-safe" by the IEC 60825-1 standard [65]. In clinical settings, however, special care must be taken with even class 1 laser devices, to ensure that no harm will be caused by concentrated light on the skin or eyes of light-sensitive patients.

Finally, we should emphasize the privacy issues that may arise as secondary to a localization solution. Health care facilities operate under the precepts of information non-disclosure to protect the privacy of personnel, patients and clients. This is an important consideration when a localization system is designed to capture images of the environment, as such images can reveal important information about the person wearing the system or about the patients and health care personnel in the vicinity. Frequently, image processing mobile localization devices are designed to send the captured image to central, computationally powerful servers for image processing. The confidentiality of the image is at great risk of being compromised while in transit over a network. Therefore, we strongly recommend against the transmission of raw images through wireless data networks. Instead, the position must be estimated by the image capturing device, and the image must be discarded immediately to minimize risk of privacy breach.

## 2.6 Localization detection based on sonic waves

Sonic waves are mechanical vibrations transmitted over a solid, liquid or gaseous medium. The distance traveled by a sonic wave can be indirectly calculated by exploiting the quasi-constant speed of such waves in air. Sonic waves produced by vibrations below and above the threshold of human hearing are known as infrasonic and ultrasonic waves, respectively.

The localization solutions grouped in this section propose the usage of ultrasonic range finders and sonars. All the articles presented herein use triangulation-based localization techniques based on the time of flight (ToF) of a sonic wave in air [58, 21, 22, 166, 175, 177, 140, 199, 127, 2, 57].

Most of the solutions in this section use a hybrid technology approach, exploiting the difference in propagation speeds of RF and ultrasonic waves [21, 22, 166, 140, 199, 127, 2]. Localization is achieved by measuring the ToF of ultrasonic waves for triangulation purposes. To achieve high localization accuracy, the transmitter and the receiver must be synchronized. An RF wave travels several orders of magnitude faster than a sonic wave. Thus, when a combination of these two types of signals is emitted in unison, the difference between the time of arrival (ToA) of the radio and sonic waves at the receiver side is a good approximation of the ToF of the sonic wave. Therefore RF waves are used for synchronization purposes, while ultrasound waves are used for triangulation purposes. When the RF synchronization signal is transmitted by a bluetooth device, the system is commonly known as BLUPS, which stands for “Bluetooth and Ultrasound Positioning System”. Two BLUPS have been included in this survey [21, 22]. We continue by presenting two distinctive examples of RF/ultrasound hybrid solutions.

Teller, Jiawen and Balakrishnan [166] extend the localization system called ‘Cricket’ [127] by making it pose-aware. The authors combined several ultrasonic receivers in a single mobile unit. The separation between each sensor in the mobile unit was fixed. The phase differences between the signal received at each sensor of the array were used to calculate the orientation of the device with respect to the transmitter. This emulates the human process of detecting the direction of an incoming sound. This extended version of Cricket located the mobile unit with sub-centimetre accuracy, and reported angle accuracies were down to a few degrees.

The localization system proposed in [140] is based on a technology called ‘the Bat’ [2, 57]. In the Bat, the ultrasound signal is emitted by the mobile device. The ceiling of the environment is instrumented with several RF transmitter-ultrasound receiver units. The ceiling mounted units were interconnected and synchronized. After simultaneously emitting a radio pulse, the ceiling units waited for a reply from the mobile stations. A mobile unit in turn sent a reply as soon as it detected a radio beacon. The creators of the Bat reported accuracies under 9 centimetres, 95% of the time.

In a different vein, three of the selected articles presented localization systems based solely on ultrasound waves [58, 175, 177]. In these solutions, wide band sonic signals were required. To achieve accurate localization, spread spectrum code division techniques were used. Spread spectrum code division allows several emitters to transmit signals, sharing the same frequency band concurrently, causing minimal interference to other signals being transmitted [119].

Hazas and Hopper [58] presented a localization system called “Dolphin” which employs broadband ultrasonic waves. The advantage of broadband ultrasound is the ability to localize a mobile station with ultrasound signals without an external synchronization system. In particular, Direct Sequence Code Division Multiplexing (DS/CDM) techniques were used to combine multiple signals simultaneously over the same frequency spectrum. The authors reported maximum localization errors of 10 centimetres 95% of the time. Along the same lines, in [177] broadband ultrasound signals and DS/CDM techniques were used for localization purposes. Beacon units were fixed at predefined positions of the environment. Such beacons transmitted a unique ID using DS/CDM. The receiver location was calculated via hyperbolic trilateration, using the difference between the time of arrival difference of time of arrival (DToA) of the signals received from the beacon. The authors reported localization errors in the millimetre range. Although the localization system was proposed for utilization on the scale of a full building, experiments were only conducted in a limited area.

### 2.6.1 Limitations

In this section we list the common challenges associated with sonic wave localization systems. Some authors reported that high levels of ambient noise commonly encumber the detection of the sonic signal [58, 22, 173]. This is particularly important when considering the deployment of a sonic localization solution for healthcare facilities, where areas of the building can be densely populated and noisy (e.g., emergency rooms or hospital foyers).

Another common issue is the co-interference caused by the presence of multiple sonic emitters in the environment. This condition encumbers the isolation of single sources. Common narrow-band ultrasound emitters may be affected by this condition [58]. The most common emitter disambiguation technique is to combine ultrasound-based triangulation with RF beacons. These composite solutions communicate the emitter ID via a different physical channel, assign time slots to multiple emitters, and thereby avoid interference at the cost of reduced accuracy.

Recent research proposes broadband ultrasonic emitters as means of overcoming the concurrent interference problem associated with narrow-band sonic sensors. The usage of a wideband signal allows for multiple access techniques such as DS/CDM, which are commonly used in telecommunication solutions (i.e., cellular phone networks. These techniques provide improved noise resilience, while allowing multiple emitting stations to transmit in synchrony over a single ultrasound channel. This eliminates the need for additional communication channels [58], reducing the complexity of the system.

All the solutions considered in this survey estimate the position of a mobile device based on the triangulation of the ToF of a sonic wave. The speed of sound over air is an important factor in such calculations. Temperature variations are known to affect the speed of sound in air [58, 21, 22, 173, 57]. Therefore, sonic wave based systems cannot be used in environments with frequent and drastic temperature or environmental changes [22].

Finally, the propagation properties of sonic waves in indoor environments pose a challenge for accurate position estimation. Elements in the environment such as furniture, walls and their salient edges cause echoes. The appearance of such echoes can lead to localization inaccuracies [22, 175, 140, 57]. Obstructions between the receiver and the transmitter can cause NLOS conditions, which contribute to erroneous distance estimates [21, 22]. The dynamic nature of healthcare facilities represents a challenge. Installation of ceiling-mounted transmitters or receivers may, to a certain extent, alleviate some of the problems associated with environmental conditions.

## 2.7 Localization detection based on inertial or mechanical sensors

The articles included in this section measure energy exerted by the mechanical movement of the element being tracked. Such energy can be measured via direct application of force, or by exploiting the inertial properties of an element of negligible mass (when compared to the mass of the object being tracked) that deflects from its fixed position within a reference frame when it is subject to acceleration or angular rotation.

Three articles were included in this section, one based on mechanical contact [108], and two based on inertial sensing [39, 138].

### 2.7.1 Localization detection based on mechanical coupling or activation

A sensory block consisting of a 60 by 60 centimetre metallic shelf was instrumented with load cells. Several sensory blocks were used as the support structure for a wooden floor. The separation between sensory blocks was of 20 centimetres. An experiment for tracking a single user was conducted, reporting a localization accuracy of 28.3 centimetres 85% of the time. Experiments were designed to track two users with intersecting paths following different walking patterns. The introduction of a second user reduced the localization accuracy during experiments involving non-intersecting paths, to 28.3 centimetres 76% of the time. The system could only differentiate between users if their weights were extremely different, i.e. the experiments were conducted with two participants, weighing 50 and 90 kilograms. Accuracy was not reported.

Similarly, in a project called "Smart Floor" [108], metallic plates were instrumented with load cells. These plates were then laid on the floor. In order to identify the person walking over a plate, the signal captured via the load cell was processed in order to select a set of 10 features. Such features emerged as distinctive for each pedestrian. The system required an off-line stage, in which the users to be identified walked over the plates of the Smart Floor. The data captured during the off-line stage served to create a database of stepping features for each user. Later, during the on-line stage, the features extracted via the load cells are matched with the features stored in the database, using a nearest-neighbour algorithm. 15 participants were tracked and identified during an experiment. The system achieved a user recognition rate of 93%. As well, the authors investigated the effects of different footwear on recognition accuracy, concluding that there as no effect. Since Smart Floor relies on mechanical contact, it can be classified as a proximity-based localization system.

### 2.7.2 Localization detection based on inertial sensors

All the articles included in this section considered a hybrid solution, combining inertial sensors with a different localization technology that provided absolute positioning information [39, 138, 24]. Since inertial sensors yield relative positioning information only, an absolute reference is required to specify the displacement reported by an inertial measurement in absolute coordinates. Inertial sensors proposed in the selected articles include gyroscopes, accelerometers and inclinometers.

Evennou and Marx [39] proposed a localization system based on an IEEE 802.11 wireless network. The absolute positional information obtained from the wireless network was combined with the relative displacements and rotations reported by a gyroscope, a dual-axis accelerometer and a pressure sensor. The information obtained from all the sensors was combined through Kalman and particle filtering [160, 9]. To calculate the displacement of the user, the accelerometer was used to count the number of steps taken. Then, a constant estimate of the stride length of the user was used to calculate the total displacement of the user within the environment. The authors showed that combining the information from the bank of sensors yielded improved localization when compared to the usage of each sensor separately. Evenou and Marx conducted an experiment using their multi-sensor localization system. The localization accuracies reported during such experiment ranged from 1.53 to 3.32 metres.

In [138], Retscher presented another multi-sensor localization system, which included inertial sensors. This system was based on a localization infrastructure named “ipos”. The system was composed of a combination of a fingerprint-based Wireless Local Area Network (WLAN) localization technology, a digital compass, a pressure sensor, and three accelerometers, plus a GPS unit for outdoor localization. Retscher characterized different brands and makes of each type of sensor. By analyzing the inertial sensors separately, localization accuracies between 5 to 8 metres were obtained. The distance traveled by the user was calculated based on stride frequency, detected through accelerometry. A pre-estimate of the stride length was used to estimate the displacement of the user. The system was reported as highly dependent on the walking patterns of each user. Finally, Retscher conducted an experiment in an indoor environment, using the wireless network localization system combined with the dead reckoning sensors, reporting approximate localization accuracies of 3 metres. Kalman filtering was invoked to combine the inputs from multiple sensors.

The solutions based on inertial sensing were classified as dead reckoning localization techniques, since the location estimates provided by such sensors depend on previous measurements to estimate the absolute position or orientation of the object being tracked at a given instant.

### 2.7.3 Limitations

One of the main issues with inertial sensors is the drift associated with thermal changes and inherent noise [39].

Drift measurement deviations are mainly caused by thermal changes in the circuitry of the sensor. The effects of such deviations can significantly affect the location estimation process. Since double integration is required to estimate the displacement of an object based on its acceleration, any small measurement error will be accumulated over time, leading to aberrant position estimation. To avoid this condition, in [39] and [138] the displacement of a user is estimated considering a constant stride length. In this case, however, the accuracy of the system is highly dependent on the walking pattern of the user.

As mentioned earlier, inertial sensors can only yield relative motion estimates. Therefore, a system that provides an absolute positional reference is required to report absolute location estimates. While an absolute positioning system could be used as the unique localization technology, the addition of the information provided by inertial sensors can lead to improved localization accuracies, as discussed earlier. Recall that solutions based on photonic and sonic sensors can be rendered unavailable due to occlusions. A dead reckoning system could be used to account for such periods of unavailability.

## 2.8 Other localization technologies

This section groups a reduced number of articles that were not included in any of the previous sections, but which matched the inclusion criteria. The sensing technologies included in this section were pressure and magnetic sensors.

Evennou and Marx [39] and Retscher (2007) [138] used atmospheric sensors as part of a multi-sensor localization system to estimate the altitude of a user. In both articles, vertical storey level accuracy is reported. In [138], Retscher characterized different commercial pressure sensors, recommending the pressure sensor PTB 220 manufactured by Vaisala. This sensor yielded an accuracy of 33 cm.

In [138], a digital compass was used in a multi-sensor localization system to assist with bearing estimation. The author reported spurious electromagnetic field disturbances that affected the readings of the compass when in proximity to metallic structures or radio wave emitting devices.

## 2.9 Discussion

A brief summary of localization principle, merits and limitations of the aforementioned technologies is presented in Table 2.1.

### 2.9.1 Recommendations

The foregoing review has suggested 1) a need for research towards rehabilitation of topographical disorientation, 2) the existence of devices for ameliorating cognitive impairments, but limited research and development of devices suitable for topographical disorientation, and 3) the existence of research towards the development of localization systems that could be incorporated into assistive technologies for topographical disorientation. In this section, we will present some recommendations to guide the selection of a suitable localization technology for assisted navigation.

Based on previous research, each type of localization system has advantages and shortcomings. By combining some of these technologies, we may exploit the advantages of the individual technologies while mitigating their respective shortcomings. Some of the selected articles in the last section have proposed effective combinations of technologies [39, 138] or mention the advantages of such composite systems [22, 5, 193, 186]. We will briefly consider the types of technologies that may be especially conducive to combination.

Recall that one of the main shortcomings of technologies based on scene scanning and triangulation techniques for localization purposes is the dynamic nature of indoor environments. Changes in the environment will diminish the efficacy of the localization algorithms used in the system. For instance, furniture or personnel agglomeration in an office could adversely affect both laser range scanners and RF systems, leading to temporary or permanent failures in localization detection. On the other hand, the self contention of dead reckoning systems allows them to provide constant tracking of the desired target because their measurements do not depend on external elements. This self contention also means that solutions based on dead reckoning will normally require calibration and acquisition of initial position and altitude. Finally, the self-contained nature of dead reckoning systems makes them prone to drifting errors, corrupting the localization information delivered by the sensors from true values [39].

Therefore the combination of a system based on scene scanning or triangulation localization techniques with a system using dead reckoning sensors would provide the strengths of both systems, allowing real time tracking of the element to be located provided by the dead reckoning sensors, even if the other localization system is unavailable due to environmental factors, while the scene scanning or triangulation-based system would provide accurate position information for recalibration purposes and a start point for initial measurements.

In fact, such a combination is present in the articles surveyed in the last section [39, 138]. The selection of technologies to be used will be dependent on the requirements imposed by the application. For instance, a solution based on RF signals would not be desirable in environments with high RF noise, or the solution proposed would conflict with elements present in the environment; for instance IEEE 802.11 access points should not be installed in the same building as medical equipment using the same frequency band reserved for medical equipment (ISM), or localization systems based on sonic waves should not be used in environments with unstable temperature conditions. Other constraints should take into account the complexity and cost of installation of a particular solution.

Certain technical challenges must be taken into account while considering the combination of multiple types of sensors to create a robust localization system. Since the localization update rates and errors associated to each type of sensor can be different, optimal schemes to combine localization data from multiple error-prone sources must be used. We can see that in fact, several algorithms of this sort are mentioned in the articles reviewed, for instance, Kalman filtering and particle filtering among other techniques. One more aspect to consider is that, the addition of elements to a system normally increase the complexity of such system, making it more prone to unavailability conditions due to failure of one or more components.

Other constraints to be taken into account are the complexity and cost of deployment of a particular solution. For instance, for some solutions the pre-existing deployment of infrastructure might reduce time and cost of implementation of a localization system. For instance, some solutions use existing unmodified IEEE 802.11 infrastructure networks [197, 191, 39, 84, 138, 83, 114, 164, 122, 12], and some others benefit from already existing video surveyance systems [123, 196].

Table 2.1: Summary of the localization technologies. The reported localization accuracies are based on typical literature values, where available. For hybrid solutions, accuracies are reported for the main technology only. († TR = Triangulation, PR = Proximity, SA = Scene Analysis, DR = Dead Reckoning)

| **Main technology** | **Technology details** | **Localization technique †** | | | | **Disadvantages** | **Advantages** | **Position** | **Orientation** |
|---|---|---|---|---|---|---|---|---|---|
| | | **TR** | **PR** | **SA** | **DR** | | | | |
| RF | Wireless Presonal and local area networks | ✔ | ✔ | ✔ | | Coarse localization, oftentimes requires an off-line phase. Sensitive to interference, signal propagation effects, and dynamic environmental changes | Usage of readily deployed equipment, reduced cost | Yes, down to a few metres | Yes, coarse: i.e. 4 orientation options |
| | Broadcast networks | ✔ | | ✔ | | For cell phones, a radio map of received power is required. For solutions based on TV broadcasts, reference stations are required | Usage of readily available infrastructure | Yes, down to tens of metres | No |
| | RFID | | ✔ | ✔ | | Limited localization accuracy. Limited range with passive tags. Battery replacement using active tags | Low tag cost, active tags are more expensive and require a battery | Yes, down to a few metres | N/A |
| | Radar | ✔ | | | | Only works with line of sight. Sensitive to reflections | Good accuracy | Yes, Submeter level | No |
| Photonic | Image processing – natural feature extraction | | | ✔ | | High processing requirements, dependence on illumination conditions and environmental noise. Sensitive to obstructions and dynamic environmental changes | High localization and orientation accuracies | Yes, submeter level | Yes, high accuracy when the cammera is mobile |
| | Image processing – fiducial markers | | | ✔ | | Deployment of fiducials requirement & measurement of their exact positions, sensitive to obstructions | Lower processing requirements when compared to natural feature extraction | Yes, submeter level | Yes, high accuracy |
| | Non-image processing based | ✔ | ✔ | ✔ | | Sensitivity to ambient noise and obstructions. Sensitivity to reflections in some cases. Affected by dynamic environmental changes | Simplicity, light weight and low cost | From room level down to submeter level | Yes, (only for one of the articles reviewed |
| Sonic, Ultrasonic | - | ✔ | | | | Most solutions require external synchronization (RF beacons). Affected by ambient noise. Accuracy affected by propagation issues and NLOS. Co-interference when using narrow band emitters. Speed of sound variations, dependent on temperature and other environmental conditions | Exxtremely high localization accuracies | Yes, down to a few centimetres | Yes |
| Inertial / Mechanical | - | | ✔ | | ✔ | Drift inherent to sensors. Relative localization, requirement of initialization and calibration | Self-containment. Resilience to environmental conditions. Continuous update of location estimates | Yes, accelerometers, accuracy dependent on recalibration frequency | Yes, gyroscopes, high accuracy, dependent on recalibration frequency |
| Other | Pressure sensors | | | | ✔ | | provides positioning information in vertical axis | Yes, vertical, submeter level | No |
| | Digital compass | | | | ✔ | Strongly affected by electromagnetic fields and metallic objects in the vicinity of the sensor, therefore not highly reliable in indoor environments | self containment | No | Yes |

# Chapter 3

# A flexible routing scheme

Torres-Solis J and Chau T (2007). *A flexible routing scheme for patients with topographical disorientation.* Journal of Neuroengineering and Rehabilitation, 4:44 (11 pages)

## 3.1 abstract

**Background:** Individuals with topographical disorientation have difficulty navigating through indoor environments. Recent literature has suggested that ambient intelligence technologies may provide patients with navigational assistance through auditory or graphical instructions delivered via embedded devices.

**Method:** We describe an automatic routing engine for such an ambient intelligence system. The method routes patients with topographical disorientation through indoor environments by repeatedly computing the route of minimal cost from the current location of the patient to a specified destination. The cost of a given path not only reflects the physical distance between end points, but also incorporates individual patient abilities, the presence of mobility-impeding physical barriers within a building and the dynamic nature of the indoor environment.

**Results:** We demonstrate the method by routing simulated patients with either topographical disorientation or physical disabilities. Additionally, we exemplify the ability to route a patient from source to destination while taking into account changes to the building interior. When compared to a random walk, the method offers potential cost-savings even when the patient follows only a subset of instructions.

**Conclusions:** The routing method presented reduces the navigational effort for patients with topographical disorientation in indoor environments, accounting for physical abilities of the patient, environmental barriers and dynamic building changes. The routing algorithm and database proposed could be integrated into wearable and mobile platforms within the context of an ambient intelligence solution.

## 3.2 Background

Topographical orientation is the ability to orient oneself within the environment and to navigate through it to specific destinations [13]. Through recent magnetic resonance imaging studies, specific structures such as the parahippocampal gyrus [163], parietal cortex [100] and temporal cortical areas [10] have been implicated as neural mechanisms for topographical orientation. It is generally agreed that in normative way-finding, humans employ a number of different way-finding strategies, including landmark recognition, route learning and map-like representations [3]. The particular choice of strategy is dependent on the individual's developmental age, the familiarity with the environment, the manner by which the environment was introduced, the level of detail in the environment and the specific navigational task at hand.

Topographical disorientation generally refers to the family of deficits in orientation and navigation in the real environment. Aguirre and D'Esposito [3] note that difficulties in way-finding may arise from a variety of different lesions or injuries and provide a well-accepted taxonomy of this disorder. For example, people living with post-traumatic effects of brain injury often have symptoms such as weakness in visual scanning skills, complex attention, prospective memory and sequential processing [90]. These symptoms can lead to problems of interaction with and perception of the surrounding environment, even several years after the injury [145],[36]. It is well recognized that topographical disorientation [180] and spatial navigation deficits [157] are common sequelae of brain injury.

Current therapies for topographical disorientation, such as simple mnemonic techniques [34] or compensatory wayfinding strategies [8], often require the presence of an occupational therapist over extended periods of time. Consequently, conventional therapies are both time and human resource intensive. Recent developments in ambient intelligence suggest that navigational support to patients with topographical disorientation among other disabilities, may be provided by smart technologies embedded in the environment and wearable devices [101, 142, 38]. An ambient intelligence (AmI) system would be aware of the patient's location and physical abilities as well as the building's structural layout. The AmI system would provide context-specific navigational assistance in the form of visual or verbal cues through an augmented reality interface. As a first step towards such a system, Chau et al. [23] reported a desktop augmented reality system for patients with acquired brain injury where pictures of navigation decision points inside a building were superimposed on the real environment to encourage the retraining of wayfinding skills. In terms of an embedded implementation, Blache et al. [17] recently proposed a full-fledged ambient intelligence navigation solution using a relational database to maintain information about the building structure and mobile entities within, a Dijkstra routing engine for navigation, WLAN for user localization and a PDA as the user interface.

In this paper, we focus specifically on the central processing module of an indoor ambient intelligence system, namely the routing engine. In particular, we address some previously unconsidered challenges of routing patients with topographical disorientation.

The Dijkstra algorithm serves to calculate the shortest path tree, originating at a single source node, to all the nodes of a connected graph. The weights associated with the edges of the connected graph must be non-negative for the Dijkstra algorithm to work. The generation of the whole routing tree from a single source with n nodes and m edges is a problem of complexity $O(n^2)$.

A common application of the Dijkstra algorithm is found in the Open Shortest Path First (OSPF) routing protocol, an dynamic interior gateway protocol used to route data packets in computer networks. OSPF is one of the most prevalent interior gateway protocol on the Internet. OSPF obtains link state information from the routers reachable in an internal network (known as an autonomous system), creating a map of such network. OSPF can detect broken links dynamically, reshaping the network map as required. The shortest path between a source and a destination router can be calculated using the network map created by the routing protocol. The metric to minimize while calculating the shortest route can be based on link reliability, available throughput, physical distance, network transmission delay or some other parameter chosen by the network designer.

When considering human routing tasks, each person has unique abilities and limitations, implying that a given environment may present different challenges to different users. Furthermore, the indoor environment may be dynamic: certain pathways may become unavailable due to facility cleaning and maintenance, renovation projects, special events or emergency closures. This is especially true in busy hospital environments. Finally, due to spatial disorientation, patients may make errors along the recommended route. These challenges imply that a single set of navigational instructions would not suffice and some form of dynamic and patient-specific routing is required.

### 3.2.1 Selective routing

In typical routing schemes such as the Routing Information Protocol (RIP) [59],[93], the Open Shortest Path First (OSPF) protocol [102],[103] or the Border Gateway Protocol version 4 (BGP-4)[137], all the routed elements (e.g., packets) are processed in a uniform manner. In the present case, however, we intend to route patients, each with unique characteristics. The minimum distance route assuming uniformly processed packets is therefore not necessarily the optimal solution.

In recent years, some authors have suggested selective routing for packet networks as a means to implement Quality of Service (QoS) mechanisms for different types of traffic on the Internet [30],[165]. These routing schemes take into account the type of traffic that the packet carries based on a tag (packet context) and the topology of the network. In other words, each packet is given individualized treatment, either on the basis of its content or to maximize network efficiency. The selective routing idea is an appealing approach to route patients based on their individual characteristics and attributes of the environment. To the best of our knowledge, selective routing of human subjects has not been previously reported in the literature.

## 3.3 Proposed method

The proposed patient routing scheme consists of a database, weighted connected graph and a routing algorithm. Each component will be described in turn.

### 3.3.1 Database

Information pertaining to patient disability, the building layout and environmental barriers along paths of travel are organized into a relational database consisting of three tables.

An adjacency table captures the building layout which is represented by a connected graph. The content of this table is the upper triangle of an adjacency matrix for the graph, coded as triplets of the form (node A, node B, ID), indicating a connection (edge) between node A and node B. The ID element is a numerical identifier which serves as a key into an accompanying context table.

A context table embodies information about environmental barriers. This table holds the attributes of each edge or link of the graph in the form of numerical weights. Example attributes include the physical distance of the link, the tread length and rise height of each step and the number of steps in a staircase, the level of illumination (luminous intensity) or the multiplicity of nearby permanent landmarks. In practice, the values of these attributes could be physically measured or derived from architectural drawings.

A patient table captures vital information about the patient, namely, personal data such as name, age, sex, contact information, and most importantly, individual ability levels. The latter were captured via a set of weights denoting the individual's ability to negotiate stairs, ramps, elevators, poor illumination and other potential barriers to mobility. A patient is defined in the database by specifying the attribute values for the fields in the patient table. For example, a patient without disability might have zero values for stair difficulty, ramp difficulty and low illumination fields while a patient with impaired mobility might have a large positive value for the stair difficulty field. In practice, the weights in the patient table might be determined from standardized assessments for gross motor function (e.g., GMFCS [113]), visual acuity or dynamic balance (e.g., center-of-mass kinematics [27]).

Figure 3.1 shows a graphical representation of a simple database with some sample fields. In our implementation, the database was implemented in MySQL.

### 3.3.2 Generation of a weighted connected graph

As alluded to earlier, a connected graph represented the target building. Deriving the graph involved strategically placing nodes and estimating weights, each of which is explained below.

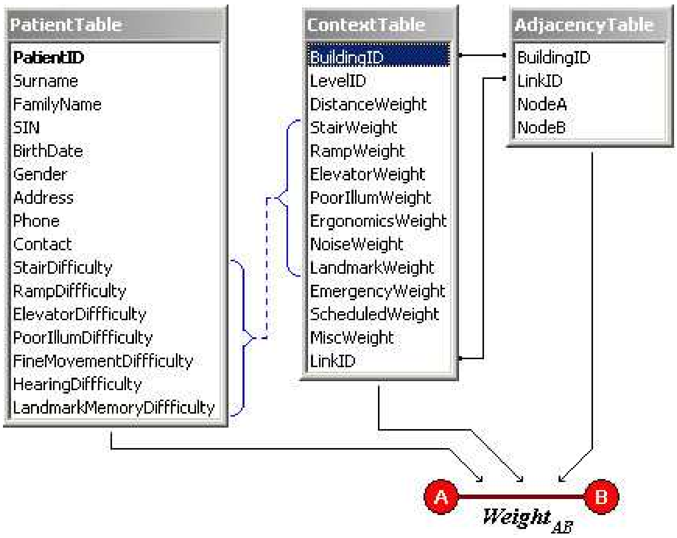

Figure 3.1: A sample database structure for the proposed method. Information from the patient and context tables are combined to generate a patient-specific weight for each link.

### Placement of nodes

Mapping schemes designed to represent a building floor plan with a connected graph have been previously proposed [135, 15, 85]. Our mapping is an adaptation of the method of Belkhous et al. [15]. In the proposed scheme, a node is placed on the floor plan at each decision point, that is, any physical space where the patient is presented with a navigational choice. Figure 3.2 exemplifies a connected graph generated from one level of a building floor plan. Nodes have been placed at decision points, which may be doorways (e.g., node 17), corners (e.g., node 38), the interior of a room (e.g., node 1) or the intersections of hallways (e.g., node 7). Several decision points can be placed in large open areas if desired.

Nodes can also be placed on either side of potential physical barriers as exemplified by nodes 19 and 32, which encompass a staircase in Figure 3.2. Placing nodes in this way, facilitates the assignment of weights to the barriers. Nodes that represent physically

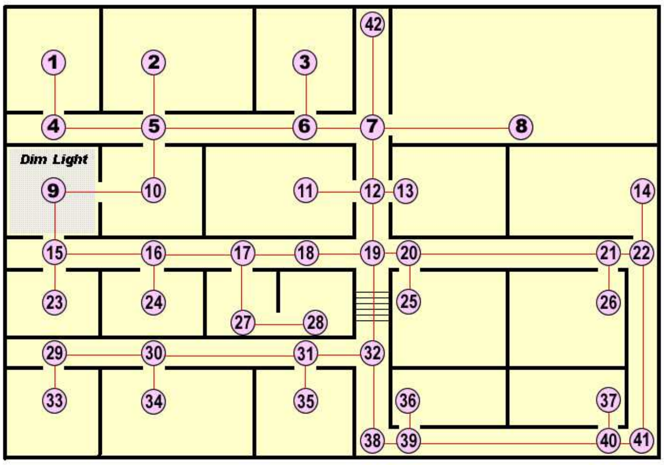

Figure 3.2: A connected graph generated from a building floor plan. This figure shows the synthetic building generated and its connected graph representation, which will be used throughout most of the subsequent experiments.

connected spaces are joined with an edge. A numerical weight is then assigned to each link as described in the next section.

### Estimation of edge weights

The weight on each link is a function of the weights for patient ability levels (patient table) and barriers in the building (context table). Generally, when a link contains an environmental barrier which unduly challenges a patient, the corresponding weight should be large. Clearly, the weight function is not unique. A simple linear function for determining the weight on a link A-B for a given patient is exemplified below.

$$\begin{aligned} Weight_{AB} &= DistanceWeight + \sum_{i=1}^{n}(BuildingBarrier_i \times PatientDifficulty_i) \qquad (3.1) \\ &+ (EmergencyFlag \times EmergencyWeight) + (TimerFlag \times ScheduledWeight) \\ &+ (MiscFlag \times MiscWeight) \end{aligned}$$

The variables correspond to the fields in the patient and context tables portrayed in

Figure 3.1 The $DistanceWeight$ represents the physical distance between nodes $A$ and $B$. The $BuildingBarrier_i$ variable corresponds to the stair, ramp, elevator or illumination weights while $PatientDifficulty_i$ denotes the corresponding patient ability level. For example, if the patient has impaired vision (high weight value for poor illumination difficulty in the patient table) and the link A-B denotes a dimly lit corridor (high weight value for poor illumination in the context table), then the product of the corresponding weights will make a large contribution to the overall weight on the link. *EmergencyFlag*, *TimerFlag* and *MiscFlag* are flags that indicate the occurrence of, respectively, an emergency code (e.g., fire), a time-dependent event (e.g., closure of a certain doorway at a specific time) and other miscellaneous situations which may affect patient routing. These flags might be toggled by alarm or monitoring systems within the building.

In this manner, the connected graph has different edge weights for different patients negotiating the same building. The final weighted graph is used in the determination of the optimal route. Evidently, links with large weights relative to those on other links are not favoured during routing.

### 3.3.3 Routing scheme

Once we have a weighted graph representing the building layout, patient abilities and environmental barriers, a routing scheme can be deployed. Different optimization algorithms have been proposed for calculating the shortest path between two connected nodes in a graph. The Dijkstra algorithm, a time-honored graph-theoretic method [35] has been widely applied for routing packets in communication networks, and is still widely used by core routers, implemented in the 'Open Shortest Path First' (OSPF) routing algorithm [102],[103]. It is also commonly applied for routing human subjects [17], mobile elements (i.e. robots) and virtual or simulated subjects in labyrinths and maps [135],[153],[15]. We therefore invoked the Dijkstra algorithm [35], which was programmed in PERL for simplicity of data management. Unlike conventional implementations that rely on a static graph, our approach uses a dynamically changing graph. Recall that there is a navigational choice at each node. Whenever the user reaches a new node, the routing algorithm references the context table in the database to obtain an up-to-date status of the indoor environment. With the current and destination nodes and most up-to-date estimation of edge weights as inputs, the algorithm returns the path of minimal cost. In this way, the "optimal" route in terms of minimal distance and best fit between environmental context and patient ability is found dynamically. Recalculating the route at every node has been previously proposed as a strategy to account for human mistakes [135]. However, previous work did not simultaneously accommodate environmental changes which may alter the building map and consequently, the graph structure.

## 3.4 Simulations

### 3.4.1 Patient simulator

We created a program to simulate a patient navigating through a building by following the directions given by the Dijkstra engine. To model patient disorientation, we defined a confusion probability, $P_C$, that is, the probability of randomly selecting the next node rather than that recommended by the Dijkstra engine. The simulation program accepts as inputs the origin and destination nodes and the confusion probability. The patient simulation program with a confusion probability, $P_C$, operated as follows.

1. The patient starts at a given source node.
2. The program generates a random number, $X$, between 0 and 1 from a uniform distribution.
   (a) If $X < P_C$, a random navigational decision is made. The program consults the interconnection map (adjacency table) to determine the number of possible paths emanating from the current node. One of the available adjacent nodes is

randomly selected as the next position of the patient. Note that it is possible that either the path suggested by the Dijkstra algorithm or the path back to the patient's previous location might be selected.

(b) Otherwise, if $X > P_C$, the navigational decision is per the Dijkstra recommendation. The Dijkstra algorithm finds the optimal route using the current node as the origin node. The simulation program consults the context table to account for any recent changes in the environment. The patient will move to the next node as indicated by the Dijkstra engine.

3. Step 2 is repeated upon arrival at each new node until the patient reaches the destination node.

### 3.4.2 Simulation of patients with topographical disorientation

A connected graph with 10 nodes and different weights for the links was constructed as shown in Figure 3.3. We simulated patients with five different confusion levels, each traveling from node 1 to node 10. The minimum distance path was $1-3-7-10$. The confusion probabilities were 0.25, 0.5, 0.75, 0.90 and 1.0. The last patient ($P_C = 1.0$) served as the benchmark subject who did not follow any navigational instructions and simply wandered randomly around the building until he stumbled upon the destination node. Wandering behaviour has been previously observed in patients with acquired brain injury [180]. Each patient was simulated 1000 times to account for route variations arising from random navigation when $P_C \neq 0$. For the patient who followed every navigational instruction, i.e., $P_C = 0$, the Dijkstra-suggested optimal path was unique and hence this patient was simulated only once. The number of nodes traversed between source and destination, the travel cost and the number of random decisions were recorded for each trial. After 1000 trials, the above data from patients with decreasing confusion probability, were compared against the random walk ($P_C = 1$) results using a Wilcoxon

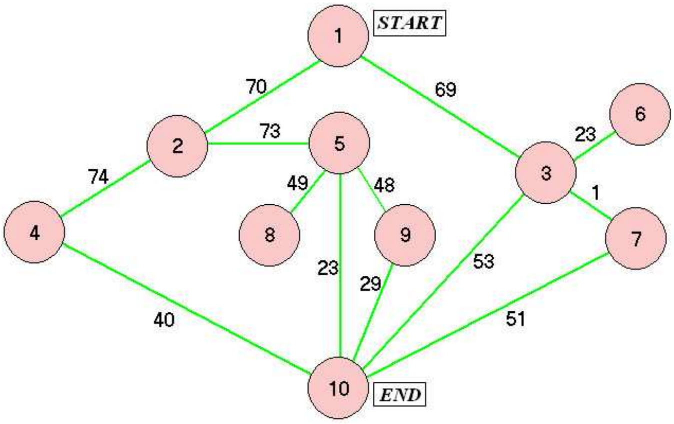

Figure 3.3: Connected graph used for routing simulated patients with topographical disorientation

rank sum test due to the non-gaussian data distributions.

### 3.4.3 Simulation of patients with physical disabilities

This experiment intended to demonstrate how the proposed routing scheme accommodates patients with different abilities. We defined three different virtual patients, all with $P_C = 0$. The first virtual patient had no impairments, i.e. null weights for all limitation attributes. The second virtual patient had a mobility limitation, with a high value for the ”stair difficulty” field in the patient table. This patient might use a mobility aid and cannot easily negotiate stairways. The third virtual patient was characterized by a high value for the ”poor illumination” field in the patient table, indicating the presence of a visual impairment. This latter patient should avoid rooms with inadequate illumination. Aside from the specified limitations, all other fields relating to patient disability were set to zero. Recall that the edge weights of the connected graph take into account patient and building attributes. Hence, each virtual patient was associated with a uniquely weighted graph representation of the building. This customization allows the routing algorithm to find the best route for a particular patient in a specific building, according to the patient's abilities and the current internal environmental conditions.

The virtual patients walked through the map depicted in Figure 3.2. In particular, we selected two paths, each of which traversed a space with a targeted physical barrier, i.e. a stairwell and a dimly lit room. The first is an environmental barrier for the patient with a mobility impairment while the second might be an environmental barrier for the patient with impaired vision.

### 3.4.4 Simulation of changing building conditions

We developed this experiment to demonstrate the algorithm's ability to correctly reroute a patient in the presence of changing building conditions. This capability could be important in an emergency situation where the number of available paths might be suddenly reduced, due, for example, to door closures. In this experiment, a simulated patient with no physical disabilities and no topographical disorientation ($P_C = 0$) walked from an origin (node 1) to a destination (node 13) in Figure 3.2. While the patient was walking, the conditions on the shortest distance path were altered, such that the weight on an upcoming link was substantially increased, i.e. the path became inaccessible.

### 3.4.5 Simulation of a complex scenario

Combining all the patient and building conditions mentioned above, we simulated a complex patient routing scenario. The patient had a confusion probability of $P_C = 0.6$ and a mobility impairment that rendered stair climbing extremely difficult (Stair Weight = 1000). The patient was asked to navigate from node 1 to node 37. In addition, building conditions were dynamic. The weight on the link between nodes 7 and 12 escalated when the patient reached node 7, forcing the routing system to find an alternate route for the patient. In addition to the recommendations from the routing algorithm, the program would reverse the patient's direction whenever the patient simulator randomly selected a link with a very large weight (999 or greater in this simulation), denoting an inaccessible or hazardous path for the patient. In a real system, this function would be enabled via a patient localization system that would detect the approach towards the restricted area and subsequently instruct the patient to reverse directions.

## 3.5 Results

The results of routing the patients with topographical disorientation are listed in Table 3.1. The histograms for the three measures in Table 3.1 were positively skewed and hence we report maximum likelihood estimates for location and spread according to a gamma distribution. We can appreciate that the patient who followed all the instructions (i.e., zero confusion probability, $P_C = 0$), arrived at the desired destination with the least effort. It is interesting to note that even patients who only followed a subset of instructions ($P_C \leq 0.75$), traversed significantly fewer nodes and experienced a lower travel cost than the patient who wandered randomly. In fact, the results suggest that as long as the patient follows at least one in ten instructions ($P_C < 0.9$), he or she will reap some cost-savings over the random walk scenario. Generally, the more prone a patient is to random navigation, the greater the effort to reach the desired destination.

We also remark that the variability of the results in Table 3.1 increases with rising confusion probability, $P_C$. Therefore, it appears that low values of $P_C$ lead to greater consistency in the selected route. Clinically, this suggests that adhering to the Dijkstra recommendations may provide the patient with a greater chance of internalizing a specific, consistent route.

Table 3.2 contains the simulation results for patients with disability. In the last two columns, the paths taken by each patient in each of the two scenarios is summarized by listing the nodes. It can be seen that each patient successfully avoided the target environmental barrier.

The simulation results for routing amid building changes is graphically represented

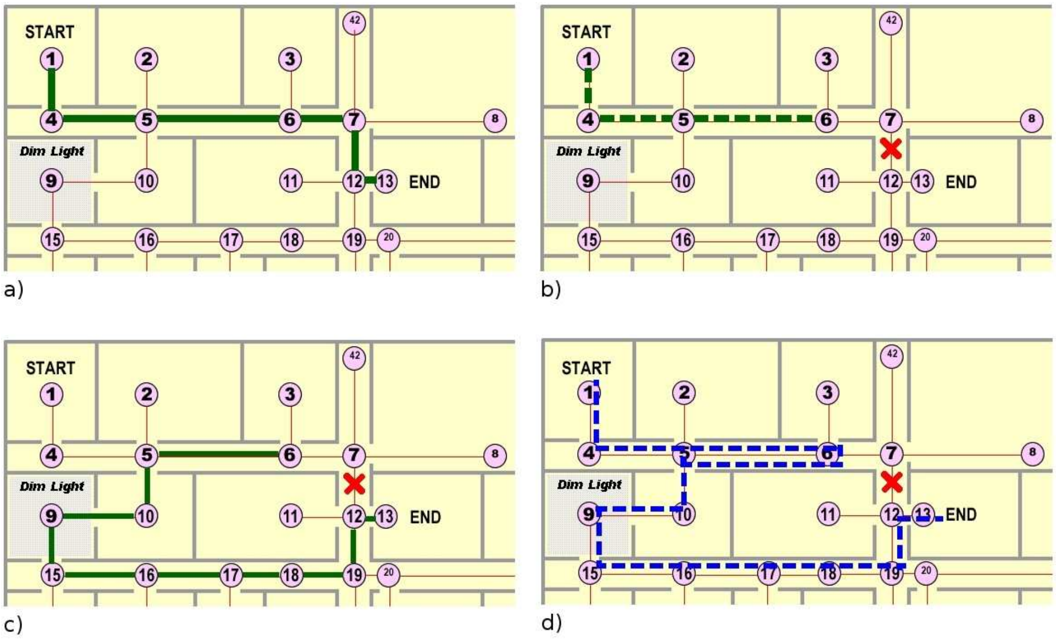

Figure 3.4: Routing results with changing building conditions. A solid line depicts the recommended route while a dashed line highlights the actual path traversed. (a) The patient is asked to walk from node 1 to node 13. The algorithm selected the optimal route as indicated. (b) When the patient reached node 6, the edge weight between nodes 7 and 12 increased to 20 times its original value. (c) At node 6 the algorithm calculated the best alternative route. (d) The final route followed by the patient.

in the four panels of Figure 3.4. Panel (a) shows the originally proposed route from the source (node 1) to the destination (node 13). This recommendation persisted until the patient reached node 6, at which point the link between nodes 7 and 12 became no longer available as seen in panel (b). Subsequently, the patient was re-routed from his current location (node 6) through the lengthy detour indicated in panel (c). The final route shown in panel (d) indicates that the patient was actually asked to partially retrace his steps in light of the building change.

A typical route-following example from the complex scenario simulation is shown in Figure 3.5. In this simulation, the link 7-12 becomes inaccessible part way through the patient's journey. The thick solid lines indicate decisions that the patient made in accordance with the routing algorithm instructions. The hashed lines indicate random navigational decisions, some of which coincided with the recommendations of the routing algorithm. We notice that the patient retraced his path in a few locations due to his random wandering. At node 7, the patient decided to go towards node 12, a link which was no longer available. Later on, at node 19, the patient attempted to access the stairway, which was an identified environmental barrier. In both of these instances, the patient was provided with the instruction to reverse his direction. Clearly, the patient did not follow to a tee his recommended shortest path i.e., 1-4-5-6-7-6-5-10-9-15-16-17-18-19-20-21-22-41-40-37 with a total cost of 1843. Nonetheless, he still reached the desired destination carving out a route that oscillated about the optimal path, racking up a final cost of 3157, which is still 38% less than the average cost of a random walk in this context.

## 3.6 Discussion

From the disorientation simulation, we see that even a patient who follows a subset of navigational directions, will benefit in terms of reduced distance and time of travel. The examples also illustrate that the proposed routing scheme can adapt to different patient abilities, environmental barriers and dynamic modifications of the indoor pathways.

### 3.6.1 Potential clinical applications

The proposed algorithm could be deployed in a patient navigation system where weights of certain links in the connected graph are automatically updated at various times in the day. Target populations would include patients with topographical disorientation, patients with different physical abilities and healthcare staff, families or visitors needing to navigate an unfamiliar indoor environment. Alternatively, the routing algorithm might

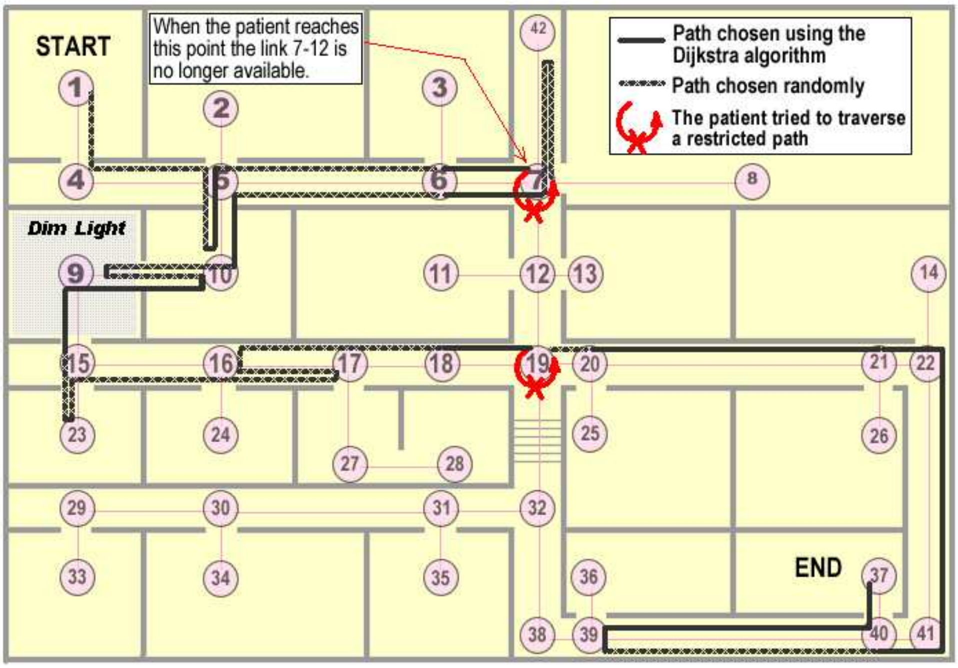

Figure 3.5: An example of the complex scenario simulation: a typical route followed by a patient with topographical disorientation and mobility impairment amid fluctuating building conditions.

be connected to an alarm system and provide a set of weights according to the nature of the emergency. For example, a link traversing elevators might have a very high weight whenever a fire alarm is triggered. A patient would then be routed away from the elevator unless there were no other navigational options for the particular patient. This might be the case for a patient who uses a wheelchair, in which case, the physical barriers of stairs would retain a higher weight than elevators even in the event of a fire.

The algorithm always recalculates the optimal route between the current and destination nodes. Therefore, assuming navigational instructions are followed, it would be known *a priori* whether or not the patient would have to traverse a link with a high weight value. The routing system, if connected to a network, could generate a message to request assistance at the forthcoming link. In this way, appropriate health care personnel could be dispatched to provide the required assistance at the specified location.

### 3.6.2 Limitations and future work

The algorithm has only been demonstrated via computer simulation with simplified patients and a subset of environmental challenges. Clinical tests with human participants are necessary to comprehensively characterize patient behaviors and potential barriers, including, for example, auditory and visual distractions, nonstationary landmarks, and crowded spaces. Also, unaccounted for at present are patient preferences, which may serve to break ties between two competing routes of otherwise equal cost. Fortunately, the proposed system is scalable in the sense that the database could easily embody additional details about the patient and the environment.

In the above examples, the graphs were generated by manual placement of nodes. In sophisticated or large scale floor plans, it may be advantageous to develop automatic graph generation methods as in the geoinformatics literature (e.g., [85]). Further, we have only described routing on a one level building. Generalizing the method for multilayer routing, for example, using 3-dimensional graphs, would be useful in hospital environments where patients are permitted limited interlevel travel.

The assignment of weights to characterize physical barriers and the patient's ability to overcome these barriers has been arbitrary in our simulations. More realistic weight determination needs to be established, as suggested through standardized assessments, building measurements and architectural drawings. Further, future work should explore a means for physicians or occupational therapists to set patient-specific weight values in an intuitive way, for example, via a series of sliders w3hose positions indicate the patient's ability to negotiate specific barriers.

In the current implementation, the patient can receive new directions only upon arrival at a new node, leaving "dead spaces" between nodes where the algorithm offers no new information. The amount of tolerable dead space would be patient and building dependent and would likely necessitate therapist assessments. Algorithmically, the spatial granularity of the information service can be easily refined by adding more intermediate nodes.

## 3.7 Conclusions

We have presented a method of routing patients with topographical disorientation through an indoor environment, accounting for physical abilities of the patient, environmental barriers and dynamic building changes. The routing algorithm and database could be integrated into wearable and mobile platforms within the context of an ambient intelligence solution.

## 3.8 Acknowledgements

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## 3.9 Competing interests

The authors declare that they have no competing interests.

## 3.10 Authors contributions

JT designed the routing algorithm. He also designed the software tools and data structures needed for the experiments. JT proposed the initial design of experiments, executed them, and analyzed and interpreted the data. JT worked on the initial draft of the manuscript. TC participated in the design and coordination of the study, experiments and data analysis, and helped to draft the manuscript. Both authors read and approved the final version of the manuscript.

Table 3.1: Simulation of patients with different levels of disorientation.

| **Confusion probability** $P_C$ | **Average no. of nodes traversed** | **Average travel cost** | **Average no. of random decisions made** |
|---|---|---|---|
| 1 (Random walk) | 6.512 (4.149) | 351.97 (237.64) | 6.512 (4.149) |
| 0.9 | 6.027 (3.561)<br>$p = 0.143$ | 315.676 (198.72)<br>$p = 0.0141$ | 5.406 (3.403)* |
| 0.75 | 5.161 (2.8593) * | 254.37 (147.65) * | 3.858 (2.92) * |
| 0.5 | 4.239 (1.9157) * | 183.54 (79.79) * | 2.109 (1.7476) * |
| 0.25 | 3.475 (1.0366) * | 144.57 (43.128) * | 0.829 (0.998) * |
| 0 | 3* | 121* | 0* |

The numbers in parentheses are the spread values according to a gamma distribution. * denotes $p << 10^{-6}$

Table 3.2: Simulation of patients with different disabilities on two routes with different barriers.

| **Patient** | **Weights** | | **Route selected** ($source \rightarrow destination$) | |
|---|---|---|---|---|
| | *Mobility limitation*[1] | *Visual limitation*[1] | *1 → 23 barrier: poor illumination @ node 9* | *8 → 36 barrier: stairs between nodes 19 and 32* |
| *Non disabled* | 0 | 0 | 1-4-5-10-9-15-23 | 8-7-12-19-32-38-39-36 |
| *Mobility impairment* | 1000 | 0 | 1-4-5-10-9-15-23 | 8-7-12-19-20-21-22-41-40-39-36 |
| *Visual impairment* | 0 | 1000 | 1-4-5-6-7-12-19-18-17-16-15-23 | 8-7-12-19-32-38-39-36 |

[1] The mobility and visual limitations were captured by the ”Stair Difficulty” and ”Poor Illumination” fields, respectively, in the patient table.

# Chapter 4

# Navigation in smart environments

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## 4.1 abstract

Topographical Disorientation (TD) is the lack or loss of orientation and navigation abilities. People living with TD face functional challenges in everyday situations. Smart mediated reality environments present potential solutions for cognitive conditions like TD. In this article, we introduce a novel mediated reality location aware environment. It was hypothesized that tools which offer different positional information affect the navigation performance of a user. The objective of this study was to investigate preferred assistive tools for indoor navigation for use in a proposed mediated reality wayfinding system. These tools may eventually be used to assist patients with TD.

To this purpose, we designed a novel wayfinding metric that can be used in the assessment of navigation tasks similar to a scavenger hunt. This novel metric is based on a relative energy expenditure ratio and is independent of navigation route complexity.

We investigated four sets of tools (minimap, locator, coordinate display and routing compass) that can be used in a smart mediated reality environment to provide relevant wayfinding information. These tools were designed using different combinations of spatial knowledge (landmark, route or survey), graphical presentation (compass, text, icon, top/side view) and reference frames (egocentric or allocentric). Each tool was evaluated objectively and subjectively. The locator and minimap tools emerged as preferred interfaces, providing the most relevant wayfinding information while minimizing energy expenditure during navigation tasks.

## 4.2 Introduction

### 4.2.1 Topographical Disorientation

Topographical orientation refers to the set of cognitive abilities that allow a person to navigate to specific destinations of an environment in an efficient way [13]. Individuals with Topographical Disorientation (TD) lack one or more orientation or navigation abilities needed to accomplish navigation tasks[3]. Some etiologies associated with TD are acquired brain injury, stroke, Alzheimer's disease and brain tumours [180, 157, 10, 111, 29].

People living with TD face functional challenges in everyday situations. Examples include limited range of mobility and loss of independence. As a result, compensatory navigation techniques, or the long-term accompaniment of a caregiver may be necessary [56, 8, 29]

### 4.2.2 Spatial knowledge

Existing literature in topographical orientation suggests three main types of spatial knowledge: landmark, route and survey [155]. Landmark knowledge is developed in early stages of spatial learning of a new environment, and it refers to the creation of mental relationships between the position of objects in the environment (landmarks) and a specific spatial location. Route knowledge refers to learning sequences of instructions required to navigate between locations that are not visually connected. Such instructions use landmarks as reference points. Finally, survey knowledge refers to a global representation of the environment. This global representation is based on knowledge of the spatial interconnection of navigable areas, and the location of objects and landmarks in the environment. This knowledge is normally acquired in the later stages of the spatial learning process. Landmark knowledge is useful for orientation (knowing one's position), while route and survey knowledge are associated with the navigation process (knowing how to reach a specific destination).

Spatial knowledge is also commonly classified as egocentric or allocentric [78]. In general, egocentric spatial knowledge refers to knowledge of the position of an object relative to the subject navigating the environment (or to an "ego object" as referred by Klatzky). Allocentric spatial knowledge refers to knowledge that is based on a coordinate system that is fixed to the environment. For instance, a north/south/east/west coordinate system is allocentric as these directions do not change for other observers when the "ego" observer rotates or moves. Knowledge of the position of a building in georeferenced coordinates is allocentric, as it will not change if the observer changes his or her position or orientation. Expressing the location of the same building as "10 meters away from me, to my left" is egocentric, as it will change with any position or orientation of the observer, and is only relevant to him/herself.

### 4.2.3 Navigation tools

For this study we consider a navigation tool to be any real or virtual device that extends or enhances the spatial knowledge or wayfinding abilities of an individual. A wide variety of such tools have been suggested in the literature. In general they can be classified into 4 main categories:

- Path-following instruction tool: A sequence of instructions is presented to the user as a textual list of turn-by-turn directions, a sequence of landmarks in the environment, or a picture or 3D model of the next location on the target path [88, 77, 32, 80].

- Virtual aids interacting with the environment: These are virtual elements added to the environment to guide users from their current location to the destination. Examples include virtual assistants that walk the user through the environment and virtual lines superimposed on the floor marking the recommended path [26, 158]. These virtual aids can be considered an extension of the path-following instructions where the point-by-point directions are embedded in the environment itself.

- Location pointing tool: A pointing device or a set of displayed coordinates indicates the position of the desired destination in 2 or 3 dimensions. Alternatively, the tool can indicate the position of a fixed point in the environment, for instance, the north pole [25]. Polar or Cartesian coordinate systems are possible displays presented in the literature [32].

- Survey maps: A map of the environment is presented, most commonly from a top-view perspective [80, 116].

### 4.2.4 Mediated reality location aware system

To investigate ways of providing technological aids to people with TD, we designed a MEdiated Reality Location Aware system (MERLA) for personal navigation. Mediated reality is defined as the modification of the real world by using computer generated elements to add virtual components (e.g., an arrow pointing towards the destination), or to occlude selective features of the real world that provide unnecessary or potentially confusing information to the task at hand (e.g., advertisements). To achieve this, a camera is used to capture the real world scene onto which these virtual elements can be overlaid or projected. Such modification of the real world is known to heighten the user's sensory experience [95, 96].

The goal of MERLA is to mitigate the need for a long term chaperon to accompany a patient on every trip. In this way, MERLA may enhance patient independence while reducing the work load of health care personnel, both of which are benefits cited in previous clinical studies of environmental interventions [187].

To reduce costs and enable rapid deployment, the system is composed of a unique fusion of off-the-shelf sensors, namely a web cam (Logitech 4000), a WiFi network USB dongle (Linksys), a gyromouse (Gyration), a Wii remote controller (Nintendo), a wearable computer (any small-factor laptop) and a mediated reality semitransparent head mounted display (Liteye LE-500).

This hardware setup is complemented by custom-developed processing algorithms that accurately determine the position of the user in the environment in real time, using visual markers and the information received from accelerometers (Wii controller) and gyroscopes (gyromouse). A total of 30 distinct visual position markers are positioned at corridor intersections throughout the building, as exemplified in Figure 4.1. Each marker consists of 17 x 17 cm, black and white, symbolic image which uniquely identifies its specific 3D location. The position and orientation of each marker are recorded in a database. The wearable webcam is used to obtain the 3D position and rotation of the camera relative to a visual marker. By combining the computed position of the wearable camera relative to a marker, and the location of that marker relative to the building (obtained from the database), we can determine the position and orientation of the user in the building. For a detailed review of the visual marker system and image processing algorithms used, the reader is referred to [73].

To reduce the number of visual markers required in the environment, the gyroscope in the gyromouse and the accelerometer in the Wii controller are used as a dead reckoning inertial navigation system (INS). This allows the position of the user to be tracked in real-time when there are no visual markers in the field of view of the camera. Markers are then used primarily to reset the absolute position of the INS which is prone to error over long periods of time without recalibration. If the building is equipped with a wireless network with multiple fixed access points, then the wireless card can also be used to increase the localization accuracy by measuring the received signal strength from nearby access points in the environment. A schematic of the wearable system and the smart environment is provided in Figure 4.1.

By wearing the proposed system, the user sees the real world, with virtual wayfinding tools superimposed in the environment, seemingly floating in front of the user. An example of this view is shown in Figure 4.2, where a virtual compass and a map of the environment are overlaid on top of the real world scene.

The objective of this article is to investigate preferred indoor visual navigational tools for use with the proposed mediated reality system. These tools may eventually be used to assist patients with TD. It is hypothesized that tools which offer different positional information differentially affect the navigation performance of a user.

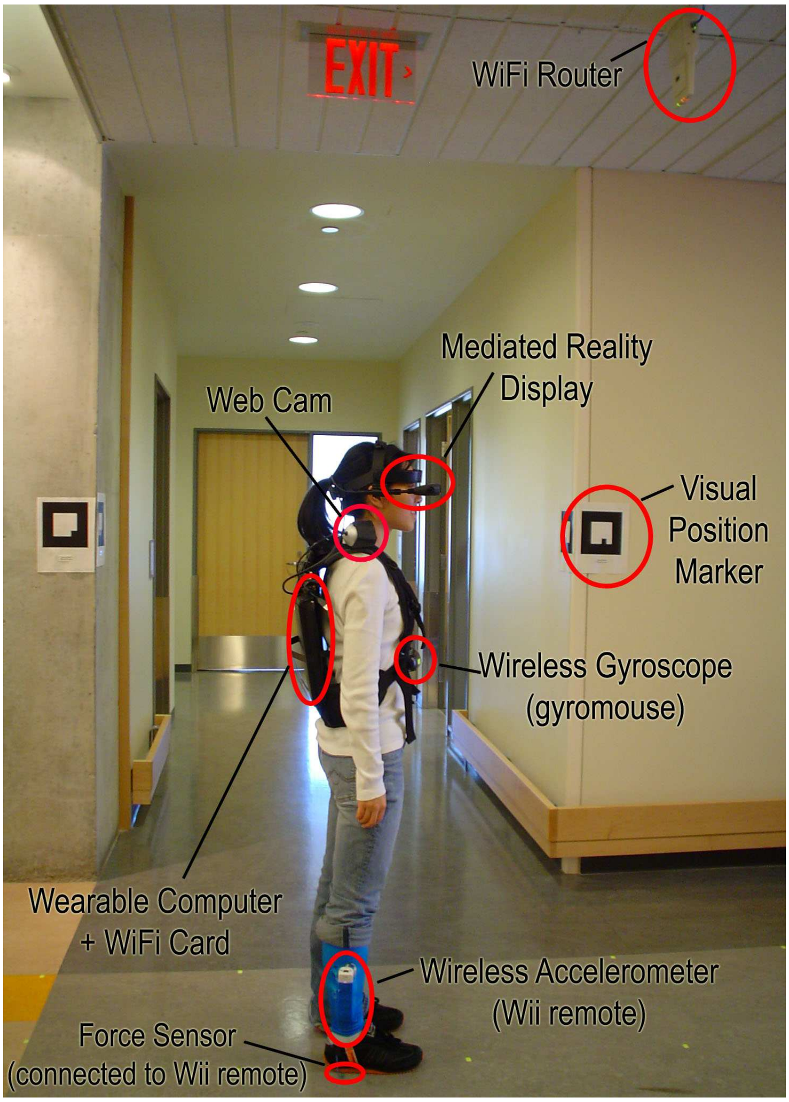


Figure 4.1: Smart mediated environment setup.

Figure 4.2: An example of what the user sees through the mediated reality display. A virtual compass (bottom-middle) and a virtual map of the environment (top-left) have been added to the real world using mediated reality.

# 4.3 Methods

## 4.3.1 Participants

For the experiments, we recruited a convenience sample of 20 participants who met the following inclusion criteria:

- 19 years or older,
- no reported cognitive impairments,
- capable of operating a computer using a mouse and a keyboard, and
- capable of understanding spoken and written English.

These criteria ensured that the participants would be cognitively mature and intact, while maximally complying to the experimental protocol.

### 4.3.2 Test environment

To test the effectiveness of different mediated reality navigation tools, experiments were conducted in a controlled virtual environment. Previous studies have shown that spatial knowledge acquired within virtual environments are transferrable to the real world [183, 42]. Since the goal of this study was to determine the preferred navigational tool irrespective of route, tools and routes were randomized to eliminate any ordering effects.

One advantage of testing in virtual environments is that confounding factors (i.e., distractions) can be well-controlled. Given the random presentation of routes and unpredictability of each user's chosen path, it would not be possibe to ensure that every user experienced equivalent distractions. Non-uniformly presented distractions would obfuscate the effects of the tools. For this reason, distractions such as path obstacles and encounters with people were not included in the virtual environment. A second advantage is that the virtual environment offers a safe milieu for human user testing. Finally, the virtual environment provides a direct linkage to the real-world MERLA system; we can simulate the vantage point of the head-mounted display used in MERLA.

To create the virtual environment we modified the source code of Quake III. Quake III is a first-person viewpoint computer game created by id Software, set in a three-dimensional environment. For our experiments we programed a new single-player game modality which we called "scavenger hunt". In the scavenger hunt, the user has to find a treasure (represented by a blue flag) present in the virtual environment. The game engine was programmed to record all movements undertaken by the user.

Our virtual environment was built and customized to simulate a hospital with 5 floors and several offices and rooms per floor. In this simulation, the operation of elevators was removed from the environment to maintain simplicity. Users moved from floor to floor by 4 flights of stairs, located at 4 opposite corners of the virtual building. We used a map editing tool called GTKRadiant, provided by id Software, to generate the customized environment.

To navigate the virtual environment, Quake III can be used with a combination of user input intefaces, namely the keyboard, the mouse and a joystick. To ensure equivalent experimental conditions, the users were requested to use uniquely the four cursor arrows of the keyboard. These keys are mapped to forwards/backwards walking and left/right body rotation.

### 4.3.3 Navigation tool design

The navigation tools were designed to provide only the fundamdental orientation information necessary to effectively guide the user to the destination. For instance, a map of the environment may contain at minimum, markers indicating the location of the user and the desired destination as minimal information. However, this tool can be extended by adding an arrow to show the orientation of the user on the map, or by changing the orientation of the map based on the user orientation. To focus attention on the effect of fundamental orientation tools, interface embellishments were intentionally avoided.

We designed four navigation tools using different combinations of spatial knowledge enhanced by the tool, presentation and reference frame. The tool characteristics are presented in Table 4.1. A picture of each tool within the virtual reality environment is shown in Figure 4.3. A description of each tool is presented below.

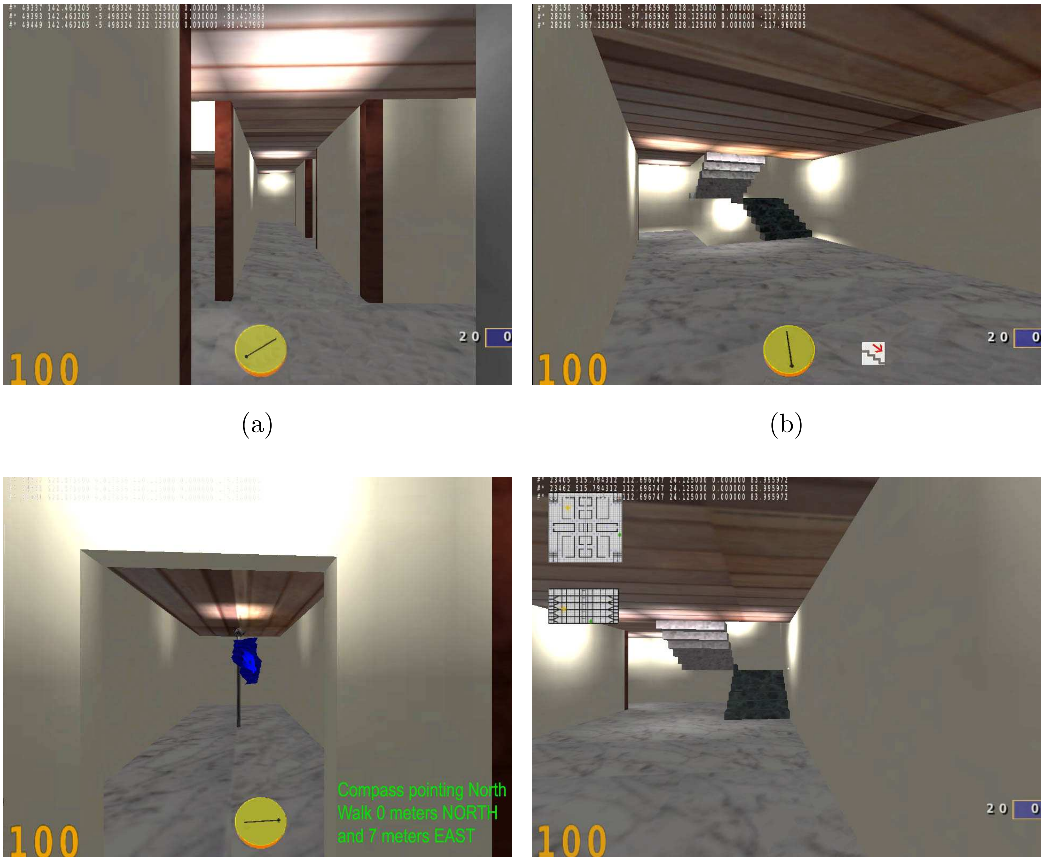
- Routing compass tool: A tool that presents path following instructions displayed as a compass. A sequence of textual instructions is hard to present in a head-up display, i.e. a transparent display that presents data without requiring the user to change the position of his or her gaze. Further presenting a picture of the environment is not desirable as in typical hospitals, many hallways look alike. We decided that the most meaningful interface to use for this tool was a compass that changes its bearing at every intersection to provide the user with turn-by-turn instructions. This tool selects and presents the best route to follow dynamically, and autoadjusts the route automatically if the user becomes disoriented or decides not to follow all the instructions as described in [170]. This tool supports egocentric spatial knowledge as it instructs the user to move forwards/backwards/left/right from the user's current position and orientation.

- Locator: A location pointing tool displayed as a combination of a compass and an icon. If the user is located on the wrong floor, an icon will appear on the head-up display indicating that the user has to go upstairs or downstairs. In this modality, the compass will point to the closest set of stairs in the building. When the user reaches the desired floor the icon will disappear and the compass will point directly to the destination point (location of the treasure). This tool supports egocentric knowledge as it provides information about the bearing of an object relative to the orientation of the user.

- Coordinate display: A location pointing tool displayed as a combination of a compass and textual information. The compass will always point to north in the virtual environment. If the user is on the wrong floor, the textual information displayed tells the user how many floors he or she has to walk upstairs or downstairs. If the user is on the same floor as the treasure the textual information displays the distance that he has to walk north/south and east/west to reach the treasure. This tool supports egocentric knowledge as it provides coordinates of the destination relative to the position of the user.

- Minimap: A tool that presents survey map information using a combination of top and side views of the building structure. Both views present the location of the user and the treasure in real time using little icons. This tool supports allocentric knowledge as it provides information about a fixed destination point in a fixed survey map.

These navigation tools were programmed as an addition to the Quake III game engine. The custom code creates 2D and 3D visual elements in virtual head-up display of the



Compass pointing North
Walk 0 meters NORTH
and 7 meters EAST

(a) (b)

(c) (d)

Figure 4.3: The proposed navigation tools. (a) Routing compass tool. (b) Locator tool. (c) Coordinate Display tool. (d) Minimap tool.

Table 4.1: navigation tools designed and their characteristics

| Tool | Type of spatial knowledge | Knowledge presented as | Tool presentation | Tool type |
|---|---|---|---|---|
| Routing compass | Route | egocentric | compass | path-following |
| Locator | Survey | egocentric | compass + icon | pointing (polar) |
| Coord. Display | Survey | egocentric | compass + text | pointing (Cartesian) |
| Minimap | Survey | allocentric | top/side view map | survey map |

game. These visual elements are superimposed in the visual field of the user and respond to changes in the user location and orientation in the game, creating the visual effect expected from each tool. For instance, the pointer of a compass changes its bearing when the user rotates his body in the game. These tools were added to the code by implementing a new C library which was linked to the game.

### 4.3.4 Experiment design

The experimental task was a scavenger hunt. The objective was to find a treasure inside the aforementioned virtual building as quickly as possible. In the ensuing description, the location of the treasure is called the target destination while a “route” is the shortest path between the user’s initial location and the target destination.

We employed routes at 3 different complexity levels. Routes of equal navigational complexity had equal path lengths, number of floors to negotiate and number of turns to reach the target destination. At each complexity level, for each participant, 5 different routes were generated with random initial user positions and target destinations, yielding a total of 15 different scavenger hunts.

We considered 5 navigation conditions: one with each of the 4 aforementioned navigational tools and one baseline scavenger hunt without the aid of any tools. In each navigation condition, participants completed 3 routes, one at each complexity level.

Custom developed software randomized the selection of routes and navigation tools, start positions and target destinations. A researcher was present during the tests to provide assistance with the experimental setup, but did not provide any navigational assistance. The participant was given a practice trial where he or she could navigate a virtual environment until comfortable with the control interface of the game. The practice environment had a different structural configuration from the one used in the actual experiments.

Before each scavenger hunt, the software would provide the user with information about the tool that was about to be used, and initial orientation information, for example, "YOU will start in the NORTH-EAST section of the building, FLOOR 5. The TREASURE is in the WEST section of the building, FLOOR 3". The scavenger hunt ended when the user touched the treasure or after 3 minutes had elapsed since the beginning of the trial. Time-stamped user position and orientation in the virtual environment were recorded thoughout the experiment.

At the end of the experiment the participant subjectively ranked the 5 tools on a scale of one (most useful) to five (least useful).

### 4.3.5 Objective navigation metric

#### Relative energy expenditure ratio $E_{RATIO}$

There are several metrics for evaluating wayfinding in virtual environments. These metrics can be classified into three main groups [147]: task performance, physical behaviour and decision making. Ideally, the metric has to be independent of route complexity. As we used three groups of routes with different complexity, distance or time (task performance metrics), these parameters themselves could not directly serve as metrics. Instead, we propose a relative energy expenditure ratio ($E_{RATIO}$), defined as the energy expended during the actual navigation task divided by the energy expended in following the shortest path, minimizing body rotations and always facing forwards. According to Ruddle's taxonomy, the relative energy expenditure ratio combines a first level metric (task performance) by considering distance travelled at a constant speed, with a second level metric (physical behaviour) by considering a "looking around" behaviour.

This combined metric is calculated using equation 4.1,

$$E_{RATIO} = \frac{\left(\frac{E_{EXPENDED}}{A_{\%}}\right)}{E_{MIN}} \tag{4.1}$$

where $E_{RATIO}$ is the relative energy expenditure for a particular scavenger hunt, $E_{EXPENDED}$ is the total energy expended by the participant during the scavenger hunt, $A_{\%}$ is the percentage of the task completed, and $E_{MIN}$ is the minimum energy required to complete the scavenger hunt, calculated by following the shortest path to the treasure using the minimum number of turns. In the following sections we will present the equations needed to obtain the value of these paremeters.

To include a third level metric (decision making), we analyzed the subjective data collected in the survey, and compared this to the objective data.

### Calculation of relative energy expenditure parameters

### Calculation of $E_{EXPENDED}$

$E_{EXPENDED}$ is the energy expended by the user during the scavenger hunt. As shown in equation (4.2), $E_{EXPENDED}$ is calculated as a linear combination of the energy expenditure of straight walking and body rotation.

$$E_{EXPENDED} = (D_{TRAVELLED} \times E_{Meter}) + \left(\frac{R_{TRAVELLED}}{\left(\frac{pi}{2}\right)} \times E_{Corner}\right) \tag{4.2}$$

where $D_{TRAVELLED}$ is the distance travelled in the virtual world by the participant during the scavenger hunt, in meters; $R_{TRAVELLED}$ is the total accumulated body rotation during the scavenger hunt in radians; $E_{Meter}$ and $E_{Corner}$ are constants representing the virtual energy expended by walking 1 meter along a straight path and the energy required to rotate the body 90 degrees, respectively. Values employed in this study were $E_{Meter} = 1$ and $E_{Corner} = 0.45$. The process of obtaining these values is presented in a subsequent section.

### Calculation of $A_{\%}$

The percentage of task completion, $A_{\%}$, takes a value of 1 if the user finds the treasure within the time limit. If the user does not reach the target destination within the imposed 3 minute limit, $A_{\%}$ was calculated by considering the point on the user's path which was closest to the treasure. Specifically,

$$A_{\%} = 1 - \frac{(D_{MIN,REMAINING} \times E_{Meter}) + \left(\frac{R_{MIN,REMAINING}}{\left(\frac{pi}{2}\right)} \times E_{Corner}\right)}{(D_{MIN,TOTAL} \times E_{Meter}) + \left(\frac{R_{MIN,TOTAL}}{\left(\frac{pi}{2}\right)} \times E_{Corner}\right)} \tag{4.3}$$

where $D_{MIN,REMAINING}$ is the remaining distance to traverse between the closest point reached by the user and the target destination (i.e., location of the treasure); $R_{MIN,REMAINING}$ is the total rotation (in radians) needed to reach the treasure from the closest point achieved by the user; $D_{MIN,TOTAL}$ is the total distance of the shortest path from the beginning of the test to the target destination; and $R_{MIN,TOTAL}$ is the total rotation required on the shortest path from the user's starting position to the target destination. To avoid division by zero in the calculation of $E_{RATIO}$ in equation (4.1), $A_{\%}$ takes values between $10^{-6}$ and 1.

Similar approaches have been used in previous studies to determine task performance based on proximity to task completion [147].

### Calculation of $E_{MIN}$

$E_{MIN}$ is the energy required to traverse the shortest path using the minimum number of body rotations. This value was calculated as

$$E_{MIN} = (D_{MIN,TOTAL} \times E_{Meter}) + \left( \frac{R_{MIN,TOTAL}}{\left(\frac{pi}{2}\right)} \times E_{Corner} \right) \tag{4.4}$$

where all the variables have been previously defined.

### Calculation of virtual energy expenditure constants: $E_{Meter}$ and $E_{Corner}$

Although energy estimates for several walking modalities are found in literature, there are no reported energy estimates for negotiating corners or rotating the body. Therefore, to obtain realistic energy expenditure values, we made indirect calorimetric measurements using the k4B2 (Cosmed), a portable metabolic cart that has been deployed in the quantification of energy expenditure during physical activity [125, 37, 152].

We designed a simple track with a long straight path and markers on the floor every 0.6 m, corresponding to the comfortable stride length of a research assistant. At the end of the straight path, we created an octagon with tape. Each side of the octagon was 0.6 m in length. The octagonal shape was selected to induce gradual turning (45 degrees per step), which is more indicative of real walking rather than an abrupt 90 degree direction change. A participant was instructed to walk to the beat of a metronome, stepping on each marker along the straight path. The metronome was used to ensure a constant walking speed, as energy expenditure is dependent on walking speed [118]. The participant repeatedly walked along the straight path until a steady state was reached (as judged by stability of $VO_2$ readings monitored using telemetry). The participant was then requested to walk around the octagon, stepping on each corner, keeping to the metronomic pace. The ocatgonal walk continued until steady state was reached. The above procedure yielded energy estimates for straight walking and turning.

The resting energy expenditure of the participant was also obtained and subtracted from steady state energy estimates for straight and octagonal walking. We found that the energy required to walk 1 meter while turning 90 degrees (2 steps along the octagonal path) is 145% of the energy required to walk 1 meter (2 steps) along the straight path. If we think of the octagonal walk as requiring energy to both walk and turn, then the energy to turn without walking would be 45% of that required to just walk 1 meter along the straight path.

We thus defined two constants, $E_{Meter}$, with a value of 1, representing the amount of virtual energy expended by walking 1 meter in the virtual environment, and $E_{Corner}$, with a value of 0.45, denoting the virtual energy expended by turning the body 90 degrees without displacement in the virtual environment.

### Statistical analyses

To test for differences in energy, $E_{RATIO}$, among tools and across route complexity levels, we invoked a 2-way repeated-measures ANOVA test, where the dependent variables were the type of tool used, and the complexity level associated with the scavenger hunt. The values were In cases of significant differences, we performed pairwise ranksum tests using a Bonferroni-corrected level of significance. Extreme outliers and positive skewness in the $E_{RATIO}$ distributions suggested the need for data correction XXX. We applied a logarithmic correction to compensate for the positively skewed data distribution.

## 4.4 Results

A full statistical report for the 2-way repeated-measures ANOVA test on logarithmically corrected data for energy expenditure, $E_{RATIO}$, is presented in Table 4.2

As suggested by the box plot in Table 4.2 and in Figure 4.4, there were no significant differences in relative energy expenditure across different route complexity levels (p=0.67). In other words, relative energy expenditure was independent of route complexity.

Table 4.2: Logarithmically corrected $E_{RATIO}$ 2-way repeated-measures ANOVA results. Dependent variables: type of navigational tool and route complexity level

| Variation source | Sum-of-squares | df | Mean square | F | p |
|---|---|---|---|---|---|
| Tool | 10.12 | 4 | 2.53 | 15.11 | 3.93E-009 |
| Complexity level | 0.24 | 2 | 0.12 | 0.85 | 0.44 |
| Tool x Complexity level | 1.01 | 8 | 0.13 | 0.66 | 0.73 |
| Tool x Subject | 12.73 | 76 | 0.17 | | |
| Complexity level x Subject | 5.34 | 38 | 0.14 | | |
| Residual | 29.1 | 152 | 0.19 | | |

In contrast, the results presented in Table 4.2 and in the box plot of Figure 4.5 indicate that there are differences in energy expenditure across different navigation tool options ($p << 0.05$). Subsequent pairwise comparisons (ranksum, Bonferroni corrected) suggest the emergence of two groups of navigation tools on the basis of energy. The first is a low energy expenditure group, comprising of the lowest energy tool, the routing compass, followed closely by the locator and the minimap. The second group, the high energy expenditure tools, includes the coordinate display and the highest energy condition, navigation without tools.

The median subjective preference rankings of the tools are shown as the cross-hatched bars in the normalized bar graph of Figure 4.6. Lower values indicate greater preference. In the same figure, we have also plotted the median energy expenditure for each tool, with lower values denoting higher energy efficiency. In this graph, the median values have been normalized by their sum across all tools, such that each data series (objective and subjective) individually sum to unity. Collectively, subjective and objective (energy) data reveal a marked user preference for the locator and minimap tools and a uniform distaste for navigation without tools. However, in contrast to the energy findings, the subjective data imply that the routing compass is not preferred.

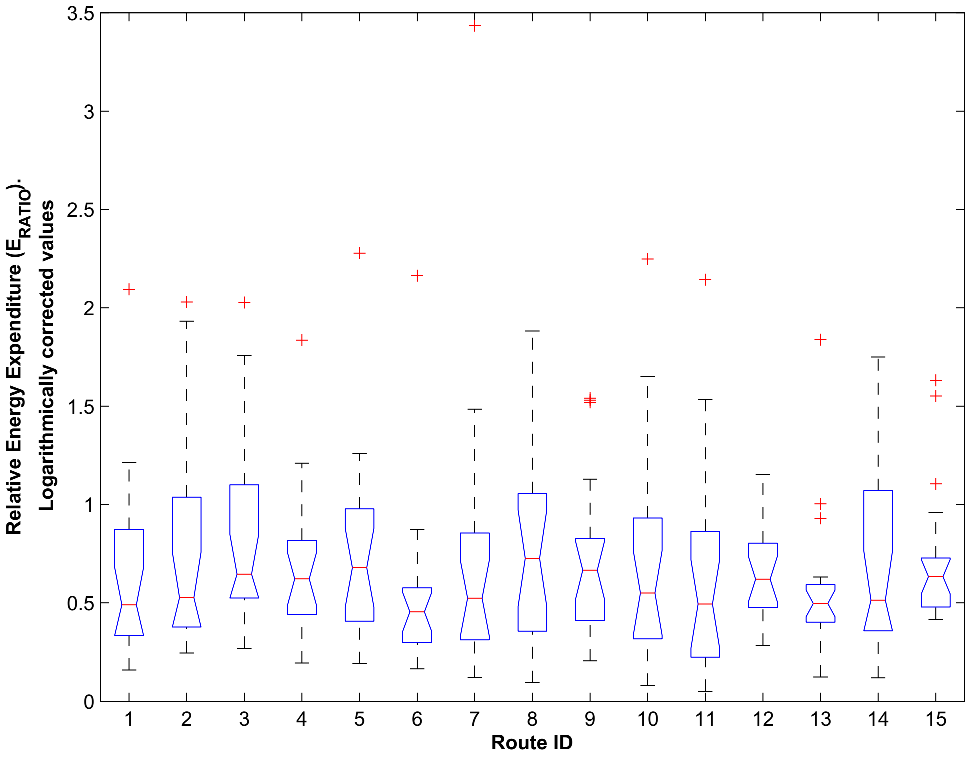


Figure 4.4: Logarithmically corrected relative energy expenditure ratio ($E_{RATIO}$) per route. Three different complexity levels were used, the three groups of routes composing each complexity level are a) 1, 4, 7, 10, 13; b) 2, 5, 8, 11, 14 and c) 3, 6, 9, 12, 15

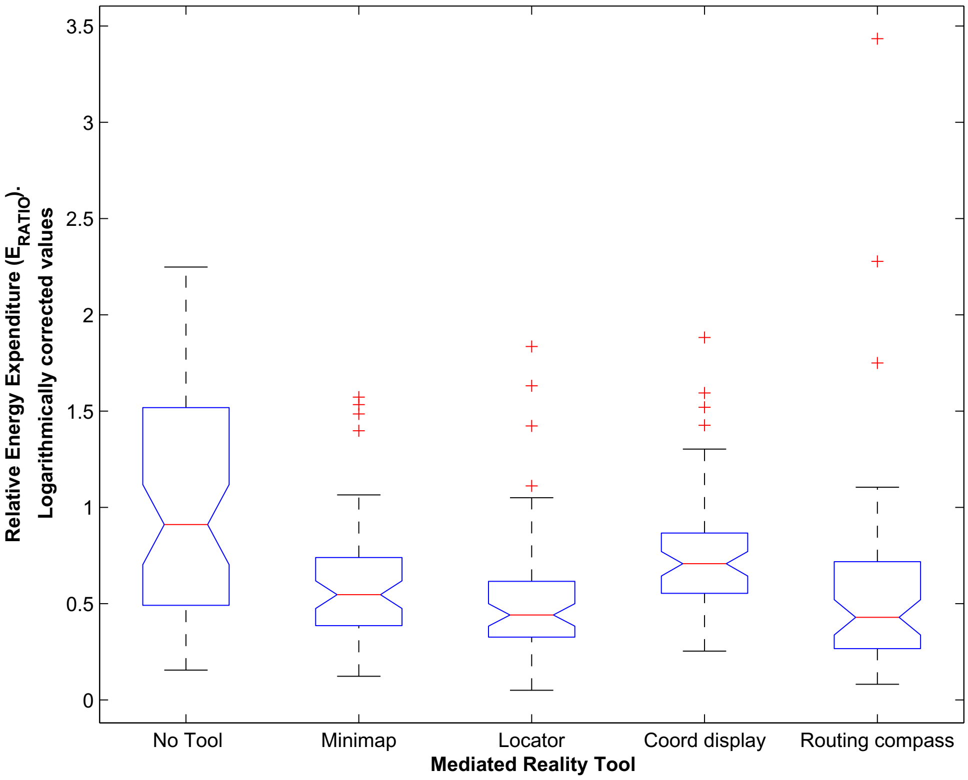


Figure 4.5: Logarithmically corrected relative energy expenditure ratio ($E_{RATIO}$) per tool.

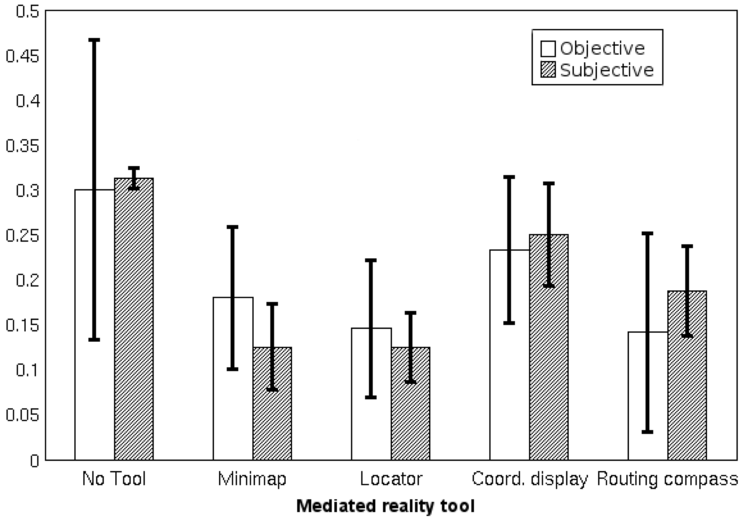


Figure 4.6: A summary of objective and subjective tool evaluations. The vertical columns represent normalized median values for each tool while the error bars are median absolute deviations.

## 4.5 Discusion

### 4.5.1 Key Findings

The finding that any tool is preferred over the no tool case suggests that all tools provided some useful, albeit limited, navigational information to the participants. Although the routing compass effectively minimized energy, it was not preferred by participants. This lack of preference may be due to the fact that the routing compass only provides just-in-time instruction, as participants approach intersections. While this knowledge is egocentric, there is no predictive information; the user has no *a priori* knowledge of the next steps and has little bearing of his or her progress towards the target destination. This lack of preemptive information may encumber the formation of mental representations of the environment, which is known to be critical for human navigation [112].

The lack of significant difference in energy across routes confirms that the energy expenditure metric is unaffected by route complexity. Likewise, the significant difference in energy among different navigational tools, confirms the hypothesis that such tools do in fact have an impact on navigational performance.

Overall the locator tool seems to provide the most relevant navigation information while minimizing the energy expended during navigation tasks based on both objective and subjective data. The minimap would be the next most preferred tool based on the same criteria. A combination of these two tools may offer a very effective navigation tool.

The study provided a novel methodology for navigational tool design and evaluation. Candidate tools were mocked up in the virtual environment, simulating the head-up display of a mediated reality navigation system. A realistic energy expenditure metric quantified differences between wayfinding performance with different tools. The systematic methodology also provided a safe environment for patient testing and, a time and resource efficient means for meaningful evaluation.

### 4.5.2 Study limitations

The experiments for this study were run in a virtual building. Due to limited ecological validity of virtual environments [89], it would be desirable to test the navigation tools during navigation tasks in a real environment. Nevertheless, the well-controlled conditions of virtual environments make them attractive for research in navigation.

The relative energy expenditure metric did not take into account the different energy requirements for walking up or downstairs. We assume equivalent cognitive effort in finding a destination one floor above or below. In studies concerned with precise energy requirements, a stair negotiation term can be added to equation (4.1) based on estimates found in literature [118].

We did not consider tools that require interaction with the virtual environment, such as virtual assistants or guide lines superimposed on the floor. When used in a mediated reality environment, interactive navigational tools require extremely accurate, low-latency localization and orientation systems to ensure correct registration of the virtual objects in the real environment [11]. Any minor inaccuracy while overlaying virtual elements on a real environment can lead to user confusion.

## 4.6 Conclusions

In this study, we evaluated 4 possible navigation tools offering different combinations of spatial knowledge (landmark, route or survey), presentation (e.g., compass, icon, text or top/side view) and reference frame (egocentric or allocentric). These tools were tested in a virtual environment and evaluated objectively using an energy-based metric, and subjectively through a simple tool ranking survey [147]. Based on objective and subjective criteria, two tools were preferred. The locator tool reinforced egocentric route spatial knowledge, and was presented as a compass. The minimap tool reinforced allocentric survey spatial knowledge, and was presented as a survey map of the environment. The development of smart environment navigation using mediated reality tools is expected to support the independent wayfinding of patients with topographical disorientation and thereby reduce the work load of health care personnel.

## 4.7 Acknowledgements

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# Chapter 5

# Pedestrian dead reckoning system

Torres-Solis J and Chau T (submitted). Wearable indoor pedestrian dead reckoning system. Pervasive and Mobile Computing, (Under review, Manuscript number: PMC-D-09-00006).

## 5.1 abstract

We introduce a wearable pedestrian indoor localization system with dynamic position correction. The system uniquely combines dead reckoning and fiducial marker-based localization schemes, exclusively using widely available, low end and low power consumer hardware components.

The proposed system was tested with various walking patterns inside a building, achieving an indoor positioning accuracy of 3.38% of the total distance walked. This accuracy is comparable to those obtained with solutions deploying specialized high cost hardware components. The low cost wearable system proposed herein could serve as the foundation for a pervasive solution for indoor way finding and patient tracking.

## 5.2 Introduction

The estimation of indoor user position is a key challenge in the development of ubiquitous computing environments because location is a fundamental aspect of a user's context [61]. A system must be location-aware in order to seamlessly deliver context-relevant information to the user [47]. Therefore, to realize a truly pervasive system, an accurate indoor positioning system is necessary.

In recent years, localization systems based on pedestrian dead reckoning (PDR) have gained interest among the scientific community. In PDR systems, position estimation is achieved by double integration of accelerometer measurements, while the orientation is estimated by integrating the angular velocity obtained from gyroscopes [169] or by obtaining the direction of the geographical north pole using magnetometers. The latter are oftentimes combined with gyroscopes, as they are prone to errors due to metallic structures and electrical appliances in the vicinity [45]. Inertial sensors (accelerometers and gyroscopes) are prone to drift errors. To mitigate such drift errors during pedestrian tracking, the properties of human gait can be exploited, resetting the velocity and acceleration values when the accelerometers are known to be static. This technique is called "zero-velocity updates" or ZUPT [45].

As mentioned in [45], most of the experiments in previous literature regarding PDR do not consider varied and realistic walking patterns. Recent research has presented PDR's capable of tracking the movements of a pedestrian without imposing restrictions on how and where a person walks. For example, Sagawa et al. [150] propose a method to measure the distance traversed without imposing constraints on speed, or stride length. This system used a combination of 3 accelerometers, a gyroscope and an atmospheric pressure sensor. The system was only tested during straight-path walking and stair climbing tasks, achieving a horizontal distance estimation error of less than 5.3% of the total distanced travelled. A PDR system capable of tracking unrestricted pedestrian movements that achieves an indoor positioning accuracy within 0.3% of the distance travelled is presented in [45]. This solution uses a hardware device named InertiaCube3, which is composed of 3 accelerometers, 3 gyroscopes and 3 magnetometers. Localization is achieved by combining the location information provided by the sensors using Kalman filters.

Other authors have considered combining PDR systems with localization systems based on external location references to recalibrate or enhance the accuracy of the dead reckoning navigation system. Recent research proposes the recalibration of inertial navigation systems for vehicles using image processing [51, 190, 50]. Of particular interest for this work are indoor pedestrian tracking solutions which combine inertial sensors and image processing. In [82] a camera was used to recalibrate an indoor localization system designed for pedestrians, using pattern classification to determine the movement performed by the user, and Kalman filtering to combine the location data provided by the sensors. The inertial tracking system was custom made, and the hardware setup was not fully described in the article. In [44] a camera was mounted on the head, pointing in the superior direction with respect to the user. Several markers were positioned on the ceiling and walls, arranged in a high density pattern of about 1.7 markers per square meters. InertiaCube2 was used as the inertial measurement device, which contains a similar sensor array to InertiaCube3, described above. The localization accuracy achieved by this system was not reported.

### 5.2.1 Motivation

Although indoor pedestrian navigation systems have been previously investigated, prior solutions require custom made hardware [82] or specialized commercial components which are expensive and not readily available to the general public. For instance, the InertiaCube family of devices have been used in [45] and [44], producing solutions in the thousands of dollars. Further, both studies only present data from a single indoor localization experiment.

Pedestrian localization applications in the fields of rehabilitation, patient monitoring or personnel tracking require solutions that are economically attractive and readily available on the market. These requirements are particularly relevant for technological solutions in developing countries, where specialized hardware is difficult to acquire or prohibitive in terms of cost [189, 188]. In light of these observations and the review above, it is clear that further research is needed to develop cost effective localization systems that allow indoor pedestrian tracking for unrestricted navigation in real-time. We hypothesized that an indoor pedestrian navigation system can be built using mainstream hardware components, while achieving position errors comparable to previously published solutions.

The specific objective of this work was to investigate an indoor pedestrian navigation system that:

- Can be easily built and deployed by using mainstream hardware components,
- Does not require major infrastructure alterations, such as the installation of wireless network equipment,
- Requires less than 1 fiducial marker per 10 square meters, and
- Yields real-time location estimates with an accuracy comparable to that of solutions found in recent literature.

The reason for limiting the amount of fiducial markers in the environment is to minimize the size of the database associated with the fiducial markers and the visual clutter, which would be unacceptable in health care facilities and public buildings. In this paper, we introduce novel features to the PDR field by proposing the usage of mainstream, low-cost hardware components in the creation of an indoor PDR system with image processing-based recalibration.

## 5.3 System Design

### 5.3.1 Hardware set-up

Our PDR system is composed of a unique combination of sensors, namely:

- A Nintendo Wii remote control to obtain tri-axial accelerometry data,
- A Gyrosense Gyropoint air mouse to obtain angular velocity from its dual-axis gyroscope,
- A Logitech QuickCam Pro 4000 web cam to detect visual markers fixed in the environment, and
- A small form factor computer with a bluetooth interface and USB ports.

To record the data acquired by the sensors, the small form factor computer was mounted on an Ergotron mobile workstand cart. A bluetooth dongle and the Gyrosense wireless receiver were connected to the computer. The laptop was pushed along by an experimenter while the subject walked on the predefined circuit.

The Wii remote control was mounted on the lateral side of the right ankle. The gyromouse was mounted anterior to the abdomen, with one sensitive axis in the superior-inferior direction and the other in the mediolateral direction. The camera was mounted on the left shoulder of the participant. Although the camera location differed from the foot location, they were spatially correlated. The data processing stage (Section 5) specifically compensated for this location difference. The hardware arrangement is presented in Figure 5.1.

Thirty distinct visual markers were positioned at the corners of a predefined polygonal indoor circuit. The walls and the ceiling of such circuit had an approximate surface of 580 square metres. This represented a marker density lower than 1 marker per 19 square metres.

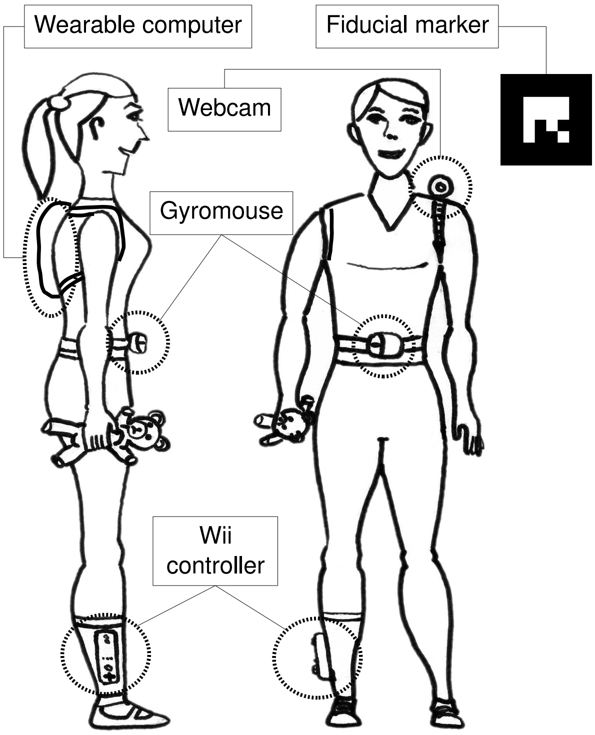

Figure 5.1: Pedestrian dead reckoning system showing wearable sensing and computing elements as well as a typical fiducial marker in the environment. The wearable computer was mounted on a mobile cart for this particular experiment (not shown).

We created a database containing the positions of each marker within the building. These marker positions were obtained with a laser distance measurement tool. The distances were measured twice and then averaged to correct for measurement deviations. A marker consisted of a letter-sized sheet of paper with a unique 17 x 17 $cm^2$ symbolic image. The visual markers and the image processing algorithms used for image localization are described in detail in [72].

### 5.3.2 Reference frames

The Wii controller was attached to the leg using a spandex sleeve to ensure intimate coupling with the limb. During gait, the tibial angle changed with respect to the axis defined by the gravitational force. Therefore, the orientation of the accelerometer axes changed with respect to the gravitational axis.

We defined two reference frames, one that was fixed with respect to the building, aligned with the gravitational force, which we call building reference frame. We use the letters X, Y and Z to label the axis of this reference frame, with Z parallel to the gravitational axis and X pointing north.

The second reference frame was fixed with respect to the Wii controller, and we call this the Wiimote reference frame. We use the letters $u$, $v$ and $w$ to label the axis for this reference frame, with w parallel to the tibia. We also define the angle $\varphi$ as the angle between the building Z axis and the Wii remote $v$ axis.

The reference frames for this study are shown in Figure 5.2.

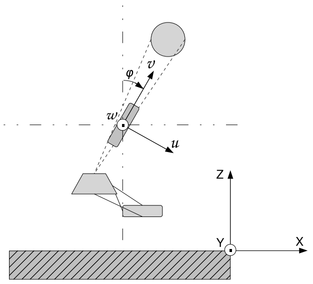

Figure 5.2: Reference frames. (X,Y,Z) are the vectors that define the building reference frame. ($u$,$v$,$w$) are the vectors that define the Wii reference frame

### 5.3.3 Software

The most important software components of the system are listed below. All software was written in C, unless specified otherwise.

- ARToolkit: library for augmented reality applications. A program was created using this library to obtain the position of the webcam relative to the markers present in the environment.

- Libcwiid: library to communicate with the Wii controller. A program was written to capture data from the Wii controller (accelerometry signals).

- Program to capture data from the Gyropoint air mouse, using the mouse data obtained from the operating system, written in C.

- Program to coordinate all the data capturing routines in a synchronized fashion, and

- Software for data analysis and processing, written in Matlab.

The ARToolkit identified fiducial markers placed in the environment. Each fiducial marker was composed of a unique arrangement of black and white squares within a 4 by 4 grid, enclosed in a black frame.

Through image processing, ARToolkit thresholds the image captured by the camera, converting it to an equivalent bynary image of black and white regions. Subsequently, the edges present in the binary image are obtained. The intersections of such edges are detected in order to find any 4 corners that compose a black square on top of a white brackround. Each black square detected in the image is compared against a set of pre-defined patterns through template matching, using a projective transformation. Such transformation allows to detect squares that are not aligned with the camera's focal axis. The parameters of the projective transformation that return a match are used to calculate the camera's distance and angle of view with respect to the detected marker, given that the marker size is previously known. The details of the operation of ARToolkit are described in more detail in [71].

We created a database of markers along with their position and orientation. In this way, we were able to calculate the absolute position of the camera in the building.

## 5.4 Experiments

An 84.4 metre indoor circuit was traversed 4 times in each direction, clockwise (CW) and counterclockwise (CCW), yielding a total of 8 trials per participant. For each trial, the participant followed a specific walking pattern (see Tables 1 and 2). Therefore, each trial or traverse of the circuit will also be referred to as a 'walking task'. Before each task, we set initial conditions for the experiment, and obtained calibration constants for the inertial sensors. The camera was calibrated only once, and recalibration was not required as long as the same camera was used for all walking tasks.

The system was tested by two participants walking at a comfortable pace. The first participant was a 30 year old, 1.81 metre tall male, weighting 72 kilograms. The second participant was a 19 year old, 1.60 metre tall female, weighting 48 kilograms.

### 5.4.1 Experiment initialization

A start point and an initial body bearing were defined for each walking direction (clockwise and counterclockwise). Pieces of tape were used to mark these starting points on the floor. The user had to position the toes of the right foot on the defined markers. This allowed us to define values for the top-view start-up position $(Pos_X[0], Pos_Y[0])$ and the initial user bearing $(\theta[0])$ in building coordinates.

Since the user started the experiment in a static position, the acceleration and velocity of the ankle relative to the building are initially equal to zero.

$V_{Ank}[0] = A_{Ank}[0] = 0$

### 5.4.2 Sensor calibration

On start-up, the user is requested to stand in a vertical position for 5 seconds. This allowed the system to obtain calibration values from the accelerometers. The values obtained during this calibration are recorded as offset constants for the accelerometers, and are named $A_{u\_OFFSET}$, $A_{v\_OFFSET}$ and $A_{w\_OFFSET}$.

The sensitivity of the accelerometers can be calculated from calibration values which are stored in the Wii remote EEPROM, in memory locations 0x16 to 0x1A. These values contain the calibrated readings for each sensitive axis when subjected to 0g and 1g accelerations, where '$g$' is the acceleration due to the gravity. We obtained the numerical relationship between Wii acceleration units and '$g$' for each sensitive axis from these values: 27 Wii accelerometer units equal 1g, or $9.8m/s^2$. We defined a conversion constant called '*Wii2MSS*', to convert Wii acceleration units to physical units of $m/s^2$,

$$Wii2MSS = \frac{9.81}{27} \tag{5.1}$$

To calibrate the gyroscopes, the user was requested to rotate the body, changing his yaw by 90 degrees to the right, and then to rotate his body back to the original orientation. The mouse ticks reported by the Gyrosense mouse upon the rotation to the right and left were accumulated in the variables $Ticks_R$ and $Ticks_L$, respectively. We calculated the sensitivity of the Gyrosense mouse in degrees per mouse tick for left and right rotations in the following fashion

$$GyroSens_R = \frac{90}{Ticks_R} \; ; \; GyroSens_L = \frac{90}{Ticks_L} \tag{5.2}$$

The camera localization system was calibrated using the software utilities provided by ARToolkit, which are explained in detail in [72].

### 5.4.3 Walking tasks

A walking task consisted of one complete traverse of the predefined circuit. For each task, the user conformed to one of the following walking patterns (each pattern was performed in both directions):

1. Walk continuously along the circuit in a natural straight path, turning only at the

corners of the circuit, until the circuit is completed (the starting point is reached again).

2. Walk continuously along the circuit in a zig-zag path until the circuit is completed.
3. Take 6 consecutive steps then stop for 5 seconds. Continue walking in this fashion until the circuit is completed.
4. Take 6 consecutive steps then stop and rotate your body to look left and right and then start walking again. Walk in this fashion until the circuit is completed.

These walking patterns were defined in order to emulate common walking behaviours of a person trying to find a place within a building.

## 5.5 Position and orientation estimation

The data obtained from the inertial sensors were processed using a localization algorithm with low memory and processing power requirements. If improved localization accuracy is required in the future, these data can be processed using advanced techniques such as Kalman or particle filtering.

To accurately track motion of a rigid body in 3D space with 6 degrees of freedom, an inertial unit, namely a combination of 3 accelerometers and 3 gyroscopes, is required [169]. In the case of an articulated body, an inertial unit has to be mounted on each articulated section of the body [97, 168]. We simplified the system by making the following assumptions:

- The ankle is articulated with respect to the pelvis, but in general the distance between the ankle and the pelvis will remain within certain limits. The movement of the torso (where the gyroscope is attached) and the legs (where the accelerometers are attached) is assumed to be spatially correlated.

- Three accelerometers can be used to calculate the total acceleration of the ankle due solely to inertia, eliminating the contribution of gravity. We can then extract forward and lateral components of the movement of the leg by using the acceleration components in each axis.

- The user of the system will be walking upright with minimal pelvic tilt. We can then use one single gyroscope to estimate the user's bearing. If this condition is not met, 3 gyroscopes would be required.

- We assume that the user walks over a horizontal plane. This means that the accumulated acceleration of the foot during a full gait cycle (i.e. heel-off to heel-off) must be equal to zero, resulting in no net vertical displacement of the foot.

### 5.5.1 Emulation of uniform data sampling

The gyromouse and the Wii remote controller have non-uniform sampling rates. We created uniformly sampled versions of the data from these sensors, simulating a sampling frequency of $F_S$=20Hz. The sampling time is the inverse of the sampling frequency (i.e. $T_S = 1/F_S$).

The Wii controller does not report data updates unless the values have changed since the last values reported (i.e. it will not send data when it is static or its movement speed is constant). We generated a uniformly sampled version of the accelerometry signals sent by the Wii controller for each uniform period $i$=1,2,3,...,N in the following fashion:

- If there were one or more Wii data reports per uniform period $i$, the last acceleration values received during that period are recorded as $A_u[i]$, $A_v[i]$ and $A_w[i]$ ;

- If the Wii remote did not send any reports during the uniform period $i$, copy the values stored from the previous period into the values of the current period

  (i.e. $A_u[i] = A_u[i-1]$; $A_v[i] = A_v[i-1]$; $A_w[i] = A_w[i-1]$)

The gyromouse only reports data if the angular velocity of any of its axis is different from zero. We generated a uniformly sampled version of the data reported by the gyroscopes in the following fashion:

- If one or more reports are received during one sampling period $i$, we assign the accumulated value of the samples received from the superior-inferior and the mediolateral sensitive axes during the period to $R_{SI}[i]$ and $R_{ML}[i]$ respectively;
- If we do not receive a report from the gyroscopes during a period $i$, we assign a value of zero to $R_{SI}[i]$ and $R_{ML}[i]$.

### 5.5.2 Acceleration, velocity and distance travelled by the ankle

As the orientation of the sensitive axis of the Wii remote changes with respect to the gravitational field during a gait cycle, we needed to consider the total inertial acceleration of the Wii remote, in order to determine the distance travelled. The three accelerometers have identical sensitivity values. This allowed us to calculate the inertial acceleration magnitude, which is independent of the orientation of the Wii remote.

$$A_{Ank}[i] = |A_u[i] - A_{u\_OFFSET}| + A_v[i] - A_{v\_OFFSET} + |A_w[i] - A_{w\_OFFSET}| \tag{5.3}$$

Technically, the ankle acceleration should be obtained via the vector sum of the orthogonal acceleration vectors. For the sake of computational efficiency however, we summed the absolute values of the magnitudes of individual acceleration components. Based on the triangle inequality, this sum is an upper bound for the magnitude of the vector sum of the three acceleration components. The absolute value bars are intentionally omitted from the second term to eliminate the accumulation of small aberrant vibrations and sensor noise in the $v$ axis.

We calculated the ankle speed relative to the ground by integrating equation (5.3)

$$V_{Ank}[i] = A_{Ank}[i] \cdot T_S + V_{Ank}[i-1] \tag{5.4}$$

where $T_s$ is again the sampling period. We then calculated the distance travelled by the ankle by double integration of equation (5.3). We converted the calculated distance to metres by multiplying the resulting value by the conversion factor '*Wii2MSS*', defined in equation (5.1).

$$D_{Ank}[i] = (A_{Ank}[i] \cdot T_S^2/2 + V_{Ank}[i-1] \cdot T_s) \cdot (\mathit{Wii2MSS}) \tag{5.5}$$

### 5.5.3 Zero-velocity updates for accelerometry signals

To mitigate the measurement drift of the accelerometers, we used a zero-velocity update (ZUPT) technique, which consists of resetting the speed and acceleration to zero when the accelerometer is known to be static, i.e., between heel-strike and toe-off of the instrumented foot. Originally we modified the Wii controller and connected a force sensor (Interllink electronics FSR, model 406) to one of the Wii controller buttons. The force sensor was placed under the heel, and was used as a foot switch. When the sensor was depressed, the acceleration and velocity values were reset to zero.

The force sensor was discontinued from the system because it is not a mainstream hardware component, and to reduce complexity since it had to be placed correctly to avoid damaging the sensor and to obtain correct measurements.

To substitute for the force sensor, we generated a synthetic foot switch signal by estimating the acceleration of the ankle due to inertia ($A_{Switch}[i]$) as the sum of the acceleration sensed by each of the three accelerometers contained in the Wii controller, namely,

$$A_{Switch}[i] = |A_u[i] - A_{u\_OFFSET}| + |A_v[i] - A_{v\_OFFSET}| + |A_w[i] - A_{w\_OFFSET}| \tag{5.6}$$

The synthetic foot switch signal was then generated using the following rule,

$$FootSwitch[i] = \begin{cases} 0, & if\, A_{Switch}[i] > A_{min} \\ 1, & if\, A_{Switch}[i] \leq A_{min} \end{cases} \tag{5.7}$$

If the value of $A_{Switch}[i]$ was lower than or equal to a minimum acceleration threshold, $A_{min}$, we assumed that the ankle was static on the ground. This minimum threshold value was selected empirically by visually comparing the synthetic foot switch signal against the signal obtained using an actual force sensor under the heel. Normally, the numerical value of the minimum acceleration would be dependent on the resolution of the analog-to-digital conversion and the sensitivity of the accelerometer. In the present study, $A_{min} = 8$, or approximately 2.9 $m/s^2$.

When the synthetic foot switch signal had a value of 1 (the switch is in a pressed state), we updated the acceleration and speed values of the ankle using the following ZUPT conditions:

$$\left.\begin{matrix} A_{Ank}[i] = 0 \\ V_{Ank}[i-1] = 0 \end{matrix}\right\}, \quad if\, FootSwitch[i] = 1 \tag{5.8}$$

Applying the ZUPT conditions provided in (5.8) to the estimation of the distance travelled by the ankle (equation (5.5)), resulted in zero displacement whenever the ankle was static on the ground. $(D_{Ank}[i] = 0,\ if FootSwitch = 1)$

### 5.5.4 User bearing

The gyroscope which has its sensitive axis parallel to the superior-inferior direction of the user reported the rate of change of the bearing of the user's torso. Therefore, the bearing of the user can be calculated by integrating the data received from this gyroscope. We used the calibration data obtained from equation (5.2) to convert the values reported by the gyromouse into degrees, $\theta$, as follows.

$$\theta[i] = \begin{cases} R_{SI}[i] * GyroSens_R + \theta[i-1] & , if\, R_{SI}[i] \leq 0 \\ R_{SI}[i] * GyroSens_L + \theta[i-1] & , if\, R_{SI}[i] > 0 \end{cases} \tag{5.9}$$

### 5.5.5 Position update rule

To calculate the absolute position of the user in the building, we combined the location information obtained independently by the camera and the inertial navigation system. The algorithm for combining the information of both subsystems worked as follows.

1. If the camera provided reliable localization information through ARToolkit, this information was preferred over the localization information obtained with the inertial navigation system. When a reliable marker was detected by the camera, the position and bearing of the user were updated using the location information from the fiducial marker system. The image obtained from the camera had an inherent delay. We empirically determined that this delay was approximately 0.5 seconds (or 10 samples at a 20Hz sampling frequency). During off-line data processing, we compensated for this delay by adding a 0.5 second time offset to the location samples obtained by the camera. If processing in real time, the last 10 position estimates can be updated upon discovery of a recognized marker in the environment.

   $Pos_X[i] = Pos_{CAM_X}[i + 10]$

   $Pos_Y[i] = Pos_{CAM_Y}[i + 10]$

   $\theta[i] = \theta_{CAM}[i + 10]$

   A marker was considered recognized if it was not discounted by the following criteria:

   (a) ARToolkit provides a recognition quality (RQ) estimate for the detected marker. This estimate takes a value between 0 and 1. An RQ value close to 0 indicates that the detected marker location is not recognized. An RQ value close to 1 indicates that the detected marker ID, position and rotation are highly recognizable. We defined an 80% threshold for the RQ estimate. Markers with RQ values under this minimum threshold were discounted.

   (b) We discounted detected markers that implied an upside-down orientation of the user (head towards the floor and feet towards the ceiling).

2. If there were no recognizable markers in the field of view of the camera, the user's position was updated each sampling period $i$, using the distance travelled by the ankle $D_{Ank}$ and the user's body bearing $\theta$ obtained from the inertial sensors in equations (5.5) and (5.9). This was done in the following fashion:

   (a) Calculate the distance travelled by the ankle in the current sampling period $D_{Ank}[i]$ using equation (5.5), correcting this calculation using the ZUPT procedure presented in equation (5.8).

   (b) Calculate the user bearing for the current sampling period $\theta[i]$ using equation (5.9).

   (c) Update the top-view position of the user in the building using these values.

   $Pos_X[i] = D_{Ank}[i] \cdot \cos(\theta[i]) + Pos_X[i-1]$

   $Pos_Y[i] = D_{Ank}[i] \cdot \sin(\theta[i]) + Pos_Y[i-1]$

## 5.6 Analysis of empirical data

### 5.6.1 Performance metrics

We calculated the path traversed by each participant using the proposed system, and we defined six metrics of interest.

1. The mean out-of-bounds error value.
2. The maximum out-of-bounds error value.
3. The difference, in metres, between the final position detected by the proposed system and the real final position.

4. The difference between the final user bearing measured using the proposed system and the real final bearing, in degrees.
5. The total distance measured by the accelerometers during each walking task.
6. The positioning accuracy.

The first two metrics are based on how often the estimated user's position fell within the boundaries of the predefined circuit during a walking task. An 'out-of-bounds' error value was calculated at each sample point. If the detected user position fell within the predefined circuit, the out-of-bounds error was zero. On the other hand, if the detected position was beyond the boundaries of the predefined circuit, the out-of-bounds error was the distance, in metres, to the closest wall of the circuit.

We calculated two versions of the first four metrics, an uncorrected version using solely the inertial sensors to calculate the position of the user, and a corrected version using the camera and the fiducial marker arrangement to adjust the position and bearing estimates during the walking task.

The indoor positioning accuracy was defined as the final position error (metric #3) over the gold standard distance, namely,

$$Accuracy = \frac{Final\,position\,error}{Gold\,standard\,distance\,travelled} \times 100 \tag{5.10}$$

where the gold standard distance in the present experiment was 84.4 m. The gold standard distance was obtained as follows. We measured the minimum and maximum distances along the predefined circuit. The minimum distance was measured over the innermost walls of the circuit, using shortcuts (diagonal walking) to minimize the measured distance. The maximum distance was measured along the outermost walls of the predefined circuit. The minimum and maximum distances along the circuit were 74.3 and 94.5 metres, respectively. The gold standard distance was taken to be the average of the maximum and minimum distances measured over the predefined path, i.e., (74.3+94.5)/2=84.4.

## 5.7 Results

The first five performance metrics for the male and female participants are presented in Tables 1 and 2, respectively.

**Table 1**: Localization metrics for 8 different walking tasks performed by the male participant. Abbreviations: CW = clockwise; CCW = counter-clockwise; UC = uncorrected measure using the Inertial sensors only; C = corrected measure using a combination of inertial sensors and image processing based recalibration.

| **Walking Pattern** | | **Mean out-of-bounds error [m]** | | **Maximum out-of-bounds error [m]** | | **Final position error [m]** | | **Final bearing error [degrees]** | | **Travelled Distance [m]** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | UC | C | UC | C | UC | C | UC | C | |
| CW | continuous | 3.47 | 2 | 8.3 | 8.28 | 11.05 | 11.18 | 11.21 | 26.06 | 87.33 |
| | zigzag | 2.65 | 0.32 | 7.25 | 4.22 | 14.83 | 3.26 | 130.95 | 13.73 | 78.15 |
| | 6 steps, 5 sec | 0.42 | 0.24 | 1.75 | 2.51 | 3.57 | 3.99 | 18.11 | 2.48 | 80.76 |
| | 6 steps, turn | 1.02 | 0.99 | 4 | 4.85 | 4.89 | 0.54 | 21.66 | 0.22 | 84.81 |
| CCW | continuous | 4.34 | 0.74 | 13.44 | 3.03 | 25.75 | 0.24 | 59.97 | 2.28 | 66.5 |
| | zigzag | 0.51 | 0.22 | 3.01 | 2.84 | 6b.83 | 0.35 | 24.62 | 15.7 | 85.68 |
| | 6steps, 5 sec | 0.68 | 0.91 | 3.65 | 5.84 | 8.39 | 0.52 | 41.53 | 18.88 | 79.17 |
| | 6 steps, turn | 2.42 | 1.77 | 6.6 | 7.5 | 21.81 | 0.35 | 111.88 | 0.5 | 79.23 |
| **AVERAGES** | | **1.94** | **0.9** | **6** | **4.88** | **12.14** | **2.55** | **52.49** | **9.98** | **80.2** |

By visually inspecting the data presented in Tables 1 and 2, we notice that the camera correction had a positive effect on the first four performance metrics for both participants. The average indoor positioning accuracy was 3.38% of the gold standard distance.

**Table 2**: Localization metrics for 8 different walking tasks performed by the female participant. Abbreviations: CW = clockwise; CCW = counter-clockwise; UC = uncorrected measure using the Inertial sensors only; C = corrected measure using a combination of inertial sensors and image processing based recalibration.

| **Walking Pattern** | | **Mean out-of-bounds error [m]** | | **Maximum out-of-bounds error [m]** | | **Final position error [m]** | | **Final bearing error [degrees]** | | **Travelled Distance [m]** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | UC | C | UC | C | UC | C | UC | C | |
| CW | continuous | 4.92 | 1.98 | 11.59 | 5.02 | 7.07 | 12.07 | 33.51 | 14.32 | 77.01 |
| | zigzag | 2.64 | 1.28 | 6.77 | 5.65 | 11.48 | 10.13 | 96.11 | 45.91 | 82.84 |
| | 6 steps, 5 sec | 1.65 | 0.26 | 6.88 | 2.42 | 11.82 | 0.88 | 43.62 | 5.71 | 65.63 |
| | 6 steps, turn | 3.11 | 1.76 | 12.28 | 11.31 | 14.22 | 0.94 | 30.58 | 7.7 | 81.71 |
| CCW | continuous | 5.99 | 1.61 | 13.27 | 6.8 | 32.7 | 0.31 | 89.28 | 15.65 | 72.4 |
| | zigzag | 1.85 | 1.57 | 7.97 | 8.25 | 27.66 | 0.18 | 165.39 | 12.57 | 73.89 |
| | 6steps, 5 sec | 2.82 | 0.92 | 6.97 | 4.92 | 5.27 | 0.33 | 31.78 | 26.84 | 66.82 |
| | 6 steps, turn | 1.97 | 1.1 | 5.2 | 3.37 | 5.46 | 0.41 | 10.96 | 7.52 | 73.21 |
| **AVERAGES** | | **3.12** | **1.31** | **8.87** | **5.97** | **14.46** | **3.15** | **62.65** | **17.03** | **74.19** |

Figure 5.3 visually depicts location estimations from three typical walks: an iterative “6 steps and stop” walk (a), a zig-zag walk (b), and two iterative “6 steps and stop” walk (a) and (c). In all graphs, the thin solid lines delineate the boundaries of the indoor circuit used in the experiments. The thin, light gray line is the estimated position using the proposed mobile dead reckoning system with inertial sensors only. The thick dark gray line is the estimated position using inertial sensors with camera correction. The dashed dark gray segments indicate where fiducial-based position and orientation correction took place.

## 5.8 Discussion

### 5.8.1 Key findings

The proposed system uniquely combines mainstream hardware to achieve real-time pedestrian indoor localization using a limited number of markers in the environment. The cost of the sensors used in this work is under $150. This makes the solution affordable for clinical applications such as the rehabilitation of indoor topographical orientation or indoor patient tracking, where GPS is not viable due to limited satellite visibility. The proposed localization system does not require major infrastructure reconfigurations, such as the installation of a wireless network. On the other hand, when wireless infrastructure already exists in the building, the accuracy of the proposed solution could be enhanced further using localization data from the wireless network.

The camera-corrected localization metrics seem to reduce the error when compared with the corresponding non-corrected metrics. This indicates that the localization accuracy improves by using camera correction while using a limited number of markers

The final positioning accuracy of 3.38% of the total distance is comparable to the positioning accuracies of 0.3% and 5.3% of the distance travelled reported in [45] and [150] respectively, both of which used Kalman filtering to estimate the position of the user. Hence, our results demonstrate that with simple processing and generic, off-the-shelf consumer hardware, indoor pedestrian localization can be achieved with accuracies comparable to those published in current literature.

### 5.8.2 Study limitations

Our experiments were conducted with a limited number of walking trials and participants. A larger variety of natural walking tasks should be conducted in the future to verify the finding that the quality of location estimation is indeed consistent across a large sample of users. In this case, the study can only be considered as exploratory and a proof of concept.

The accuracy of the proposed system is limited due to the simplified processing algorithm used and could be further improved by using more complex tracking algorithms, such as Kalman filtering as in [45, 82] or algorithms that take into account the structure of the building, such as particle filtering. This could be the subject of future research.

The localization algorithm assumed that the user walks on a horizontal surface. If the vertical location of the user needs to be tracked as well, a barometer could be added to the sensor bank.

The dead reckoning localization algorithm used in this study only takes into account the total acceleration experienced by the ankle, assuming that the step was taken forwards. To determine the direction of the step (i.e., steps taken backwards or laterally), the signals obtained from the different axes of the accelerometer need to be analyzed individually. For example, the proposed system may benefit from a step classification algorithm similar to the one used in [82].

We noticed that the distance calculated by the system was often shorter than the minimum distance required to fully traverse the predefined circuit. In fact, 6 distance measurements out of 16 were below this minimum distance. Possible causes include inaccuracies in the simulated foot switch used for zero-velocity updates and the difference between the distance travelled by the foot versus the distance travelled by the ankle. Therefore, location estimation might be improved in future research by developing a more accurate foot switch signal from the accelerometry data, and compensating for the difference in the distance travelled by the foot and the ankle.

We also noticed that the orientation provided by a single gyroscope was not enough to reliably track the orientation of the user in some cases. This could have been due to the violation of the assumption that the users walked with minimum pelvic tilt. If such condition is not obeyed, the sensitive axis of the gyroscope considered for data collection might have capture rotation data of the user's body that did not correspond to the vertical (gravitational) axis. Although the camera correction algorithm seemed to account for this type of errors, the accuracy of orientation detection could be drastically improved by used a tri-axial gyroscope. A better solution would be combining the gyroscopes and the accelerometers in one single rigid unit (probably worn in the ankle), too create a unit similar to InertiaCube. This option might be explored in future experiments using the Wii Motion Plus extension for the Nintendo Wii remote controller, which contains a two-axial gyroscope.

## 5.9 Conclusions

The proposed localization system yields indoor positioning accuracies that are comparable to those of previous works on indoor navigation and outdoor GPS-based localization, while being cost-effective and reliant only on mainstream consumer hardware components. Our system uniquely combines dead reckoning sensors for position estimation and fiducial marker-based image processing localization for dynamic recalibration. The proposed system can estimate user locations for four different level-walking tasks without constraining walking speed or stride length. Future research may aim to further improve the localization accuracy of the proposed system and conduct expanded tests with a larger sample of participants.

## 5.10 Acknowledgements

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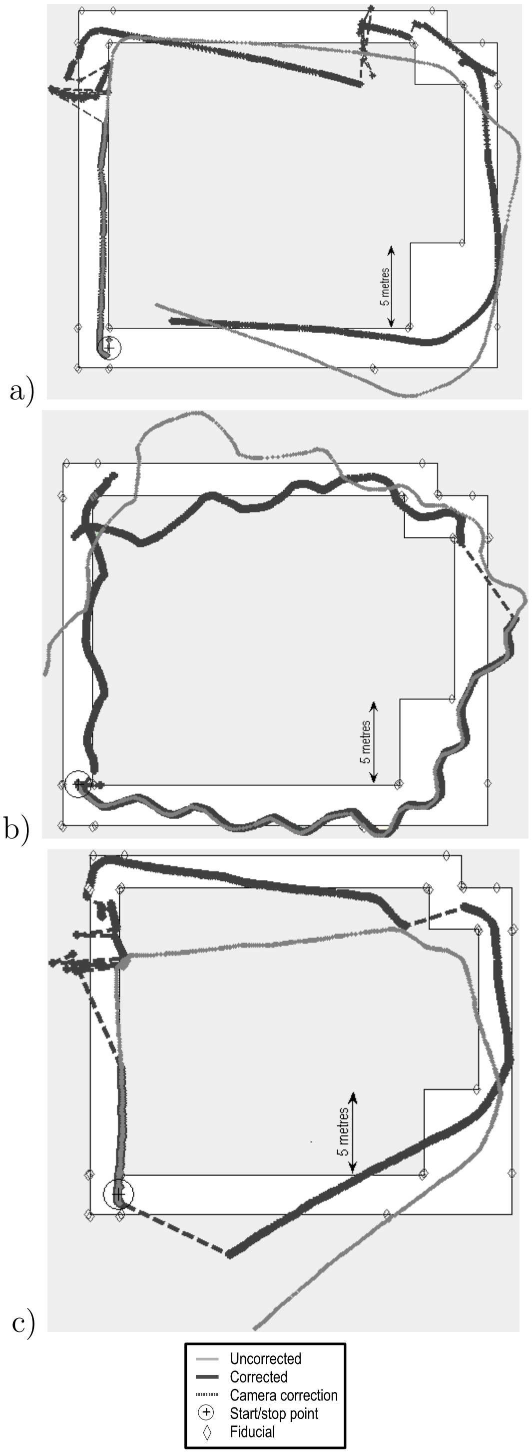

Figure 5.3: Examples of typical location estimation trials showing boundaries of the indoor circuit, the estimated path using inertial sensors alone (thin light gray line), the estimated path with camera correction (thick dark gray line) and the jumps in estimated position due to camera correction (dashed line). (a) clockwise, “6 steps and stop” walk, male participant; (b) counterclockwise, zig-zag walk, male participant; (c) clockwise, “6 steps and stop” walk, female participant.

# Chapter 6

# Mediated Reality Location Aware System (MERLA)

Tores-Solis J and Chau T (submitted). *A mediated reality location aware (MERLA) system to facilitate indoor topographical orientation.* Journal of Location Based Services. Manuscript number: TLBS-2009-0016

## 6.1 abstract

We introduce a Mediated Reality Localization Aware (MERLA) system that offers wayfinding tools for human indoor navigation. We hypothesized that indoor topographical orientation skills can be enhanced by using the MERLA system. To quantitatively test this hypothesis, six subjects participated in an experiment consisting of 24 scavenger hunts inside an unfamiliar hospital building. For each scavenger hunt, the user was randomly offered either no tools or one of two navigational tools: a locator or a minimap. The 8 no-tool trials constituted the baseline condition. To mitigate spatial learning effects over the course of the experiment, participants were blindfolded and transported to a random start location before each scavenger hunt. We estimated the relative energy expended by each participant per hunt and each participant completed a post-experiment survey.

Results indicated that when aided by mediated reality tools, participants expended significantly less energy than in the unaided condition (p=$4 \times 10^{-6}$). Energy estimates confirmed that spatial learning when using the tools was negligible over the duration of the experiment. Collectively, objective and subjective results revealed a strong user preference for navigation with tools (either the locator or the minimap) over navigation without tools. The MERLA system, presented in this study, may offer a platform for the future development of assistive devices that improve the independence of people with topographical disorientation.

## 6.2 Introduction

Topographical orientation is the ability of recognizing objects and places in the environment, forming mental spatial relationships between them, and being able to navigate to one of these objects or places efficiently [16]. Topographical disorientation refers to deficits in orientation and navigation in the real environment [3]. An individual with topographical disorientation can find it difficult to relate the position of an object with respect to him or herself or to a landmark, has difficulties recognizing landmarks, or has impaired ability to learn paths between objects and places [146]. All of these challenges can lead to the inability to navigate through the environment independently.

Outdoor navigation tools that facilitate topographical orientation, such as compasses or global positioning system devices (GPS), are commonplace and commercially available. However, indoor navigational tools are still in the research stage. Recent studies have investigated the effectiveness of navigation tools within indoor virtual environments [146, 172, 117]. [88] evaluated the benefits of navigational tools in real indoor environments. However, the location tracking and tool display decisions in their experiments were not automatic, but manually facilitated by the experimenters. Other authors have proposed indoor, location-based, augmented reality systems delivered via head-mounted displays [136, 134, 53]. [136] described an innovative localization system that combined optical tracking of environmental fiducial markers with user-based inertial tracking, but did not present any empirical data. Deploying an indoor ultrasound location system with their augmented reality headgear, [134] presented qualitative user comments which supported improved user-environment interaction experience via in-situ visualization. Their focus however was not on navigation. Most recently, within a very small indoor maze and using a limited range tracking system, [53] demonstrated that when wearing a battlefield augmented reality system, participants more comprehensively covered the maze than when navigating unassisted.

In the spirit of [88] and building on the optical-inertial hybrid tracking approach [136], we created a Mediated Reality Location Aware (MERLA) device [171] to study the effects of indoor navigational tools on actual wayfinding performance. Mediated reality refers to the augmentation (i.e., augmented reality), reduction (i.e., diminished reality), or otherwise alteration of the visual perception of reality [94]. Typically, the real world scene is captured by a camera, processed and subsequently presented to the user. The user then perceives the modified real world scene, which may contain virtual elements whose dynamic behavior is location-based. Since mediated reality can enhance user experience and perception [95, 96], it appears to be a fitting platform for presenting indoor navigational tools to the user.

It is important to mention that an alternate indoor navigation assistive alternative proposed in the literature is the usage of robotic guidance assistants [126]. This seems to be a promising alternative since autonomous robotic navigation has been extensively explored and tested. Nevertheless, we did not consider the usage of robotic guidance assistants in this study for the same reasons exposed in chapter 4. Virtual navigation assistants would introduce several variables that would encumber data analysis and result interpretation. This option could be explored in future studies.

The objective of this study was to determine if topographical orientation within a large unfamiliar indoor environment can be enhanced by a location-based device which presents the user with one of two different mediated-reality navigational tools, i.e., a locator and a minimap. The selected tools had been previously identified as the preferred navigational devices in a virtual environment study [172]. Unlike previous studies, we focus specifically on the user's physical effort when navigating with a fully-automated and integrated location-based wayfinding service. Furthermore, we consider a much larger navigation area than in previous indoor investigations. Research in this field may lead to the creation of assistive devices that improve the independence of people with topographical disorientation [88].

## 6.3 Methods

### 6.3.1 Participants

We recruited a convenience sample of six participants (3 male) from the community, who met the following inclusion criteria:

- 18 years of age or older
- Normal or corrected to normal vision
- Unfamiliar with the building where the experiments took place
- No reported cognitive impairments
- Capable of providing navigational instructions in English

### 6.3.2 Reference frames

The MERLA system obtained estimates of the location and orientation of a person within a contemporary hospital building. For this, we considered three different reference frames.

1. The building reference frame (fixed with respect to the building): We use the letters (X,Y,Z) to label the axes of this reference frame, with ‘X’ pointing east, ‘Y’ pointing North, and ‘Z’ pointing upwards.

2. The wheelchair reference frame (fixed with respect to the wheelchair): We use the letters (u,v,w) to label the axes of this reference frame. The origin was defined to be the centre of the seat upholstery of the wheelchair, with ‘u’ pointing to the front of the wheelchair, ‘v’ pointing towards the right side of the wheelchair and ‘w’ pointing upwards with respect to the wheelchair. The bearing of the wheelchair in the building was defined as the angle between the ‘X’ and ‘v’ axes, projected on the XY plane.

3. The marker reference frame: MERLA used a fiducial marker recognition system, and the ARToolkit library [72] to estimate the position and orientation of a camera with respect to the fiducial marker in the camera’s field of view. Each marker had its own reference frame, as defined in [72].

### 6.3.3 Localization system

For indoor user localization, we used a dead reckoning system combined with a fiducial image processing system for intermittent position correction, similar to that proposed in [171]. The basic idea is that strategically placed fiducial markers are intermittently captured via a camera to provide the absolute position of the user, while the dead reckoning (inertial) system estimates the user’s relative position between fiducial markers. The system was designed to provide real-time location estimates.

Due to safety requirements imposed by the healthcare facility, participants were required to use a wheelchair. Since the inertial dead reckoning subsystem proposed in [171] relied on gait features for sensor recalibration, we developed an alternative solution suitable for wheeled mobility. In particular, the spokes of the back wheels of the wheelchair were instrumented with magnets (See Figure 6.2). Two magnetic sensors (Filzer dZ2L) were set on the wheelchair frame close to each wheel. Two sensors per wheel were required to determine the direction of motion (forwards or backwards). Knowing the radius of the wheels, the number of spokes per wheel, and the distance between the wheels, we calculated the displacement and the change in bearing of the wheelchair each time the spoke-mounted magnets passed the frame sensors.

Each fiducial marker was composed of a unique arrangement of black and white squares within a 4 by 4 grid, enclosed in a black frame. The web camera used for the fiducial-based localization system was mounted on the right handgrip of the wheelchair, facing towards the front of the wheelchair. The fiducial recognition system was more prone to misrecognizing a marker as the number of distinct markers grew. Hence, to mitigate identification errors, we used only 10 distinct markers, but marked each position in the building with a pair of markers. Each marker pair represented a numeric ID composed of two digits. For instance, the combination of marker 4 on top and marker 3 on the bottom identified position 43 in the building. This position ID could then be used to retrieve the building coordinates of the marker set within the building from a database of the exact position and orientation of each fiducial within the building. Ninety-two fiducial marker pairs were fixed at the corners of the intersections and on the walls of large areas of the building. This represents a density of less than 1 fiducial per 15 square meters of wall and ceiling surface of navigable areas.

To further reduce fiducial detection errors, our algorithm verified that

- the separation between two markers in a set was 29.5 cm, which is the length of a sheet of letter-sized paper;
- both markers in the set had their ‘y’ axis (as defined in the ARToolkit marker reference frames [72]) aligned with the ‘Z’ axis of the building, and
- the vector traced from the first to the second marker in the set pointed to the

ground.

The fiducial identification errors were noticeably reduced in preliminary tests using this algorithm. The entire location estimation system consisting of the dead reckoning and fiducial tracking subsystems, was programmed in C.

### 6.3.4 Mediated reality navigation tools

The navigational tools used in the experiments were the locator (Figure 6.1a) and the minimap (Figure 6.1b). The locator was a 3-dimensional wedge that always pointed in the direction of the treasure. The minimap tool consisted of a top-view of the experimental area, showing the orientation and position of the wheelchair (as an arrow) and the location of the treasure (as a star). These two tools were selected because they were the most preferred in terms of energy expenditure and subjective ratings in a previous virtual environment navigation study [172].

In a given trial, the selected tool was superimposed on the participant's field of view using a Liteye 500 monocular see-through head-mounted display. Examples of the participant's augmented perception of the environment through the MERLA system are presented in Figure 6.1. The navigational tools were also programmed in C, using the graphic libraries provided by SDL and OpenGL. The complete MERLA system processed and displayed information to the user via a wheelchair-mounted laptop, with no perceptible delay. The instrumentation constituting the MERLA system is highlighted in Figure 6.2.

### 6.3.5 Test environment

Indoor navigation experiments were conducted on the fourth floor of a rehabilitation hospital, which has an approximate area of 3300 square meters. Publicly accessible areas and several rooms of the building were used in the navigation experiments. The starting

Figure 6.1: Examples of the mediated-reality tools, as perceived by the participant. a) The locator tool acts like a compass pointing to the treasure. In this example, the user needs to walk forwards and to the left to reach the treasure, resulting in a NW orientation of the locator. b) The minimap tool represents the position and orientation of the wheelchair as an arrow in the map, while the treasure is depicted as a star. In both examples, the "treasure" label was not seen by the user; it has been added simply to highlight the location of the treasure within these images.

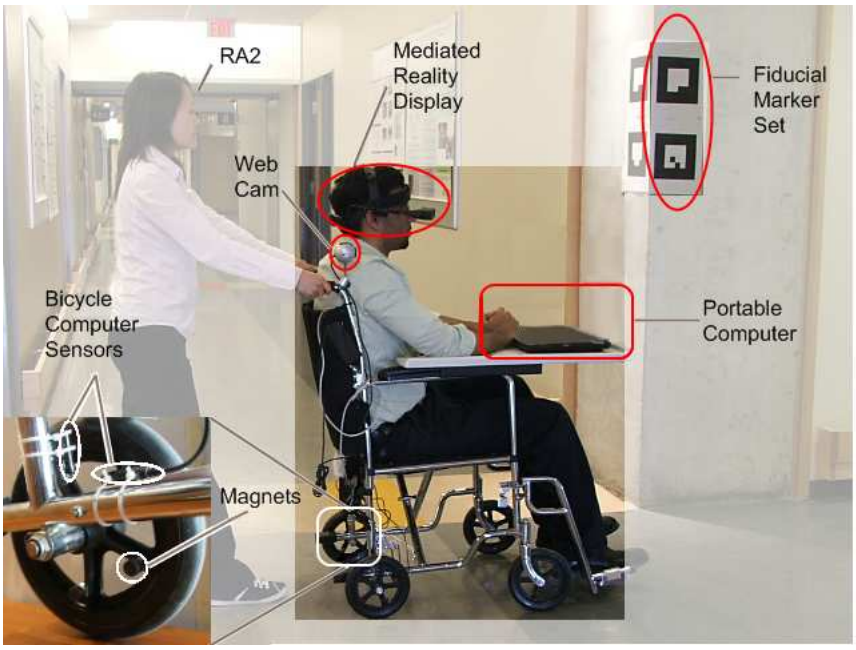

Figure 6.2: A section of the experimental environment, showing the instrumentation deployed, the participant and the research assistant in charge of pushing the wheelchair (RA2).

and ending locations of all the possible navigational routes were marked on a floorplan of the building. Two research assistants were familiarized with the building and the predefined locations in the floorplan. The test environment is depicted in Figure 6.2.

### 6.3.6 Experiment design

The experiment consisted of 24 scavenger hunts. The objective of each hunt was to find a treasure, a 30 x 30 x 15 cm box, covered with bright orange flag tape. Each scavenger hunt had a predefined start point, initial wheelchair bearing, and target destination, i.e., treasure location. These locations were selected such that the navigational complexity from the participant's initial location to the treasure was equivalent for all scavenger hunts. Navigational complexity was estimated by a measure which incorporated the distance traversed and the number of body rotations required to navigate from the start point to the treasure position, as defined in [172].

The order of presentation of the different scavenger hunts was randomized. The indoor navigational tool in each scavenger hunt was randomized in the following fashion:

- A sample space N, M, L was defined, representing the possible tool choices "No tools", "Minimap" or "Locator", respectively.
- An event pool with 24 tools was defined. These 24 tools were composed of each possible outcome 'N', 'M' and 'L' repeated 8 times each.
- For each scavenger hunt we randomly sampled the event pool without replacement. The selected sample defined the tool for that particular scavenger hunt.

Before starting the experiment, the treasure was shown to the participant. The participant was familiarized with the two navigational tools; pictures of the minimap and a quick demo of the locator were provided to the participant while he was on the first floor, which was not part of the test environment.

To mitigate spatial learning effects, the participant was blindfolded before being transported by wheelchair to the fourth floor via the elevator. The participant was also blindfolded before starting each scavenger hunt, while being transported to the predefined start location. The wheelchair was rotated a few times to disorient the participant before setting it to the predefined start orientation for the scavenger hunt. Before the start of each scavenger hunt, a research assistant (RA1) placed the treasure in the predefined target location for the specific hunt and vacated the area as soon as possible to avoid revealing the treasure location. A second research assistant (RA2), shown in Figure 6.2, was informed of the starting location and orientation of the wheelchair for the scavenger hunt but had no knowledge of the treasure location.

At the beginning of each scavenger hunt, the participant was asked to remove the blindfold. If a navigational tool was offered for that scavenger hunt, the participant adjusted the augmented reality helmet until he or she could see the tool. RA2 pushed the wheelchair according to the participant's commands. The permissible commands were “forward”, “left”, “right”, “turn around”, “stop”, and “recalibrate”. RA2 carried out the first four commands, continuing to move in the stated direction until finding a new intersection or an open door, or upon an explicit “stop” command. The participant was able to request recalibration if he or she thought that the navigational tool displayed inaccurate or confusing information. To recalibrate, the participant needed to issue the “recalibrate” command, and point to a set of fiducials. In this case, RA2 positioned the wheelchair to face the pair of fiducials indicated by the participant and awaited further instructions.

If the participant spotted the treasure within 10 minutes, the wheelchair was pushed to the treasure location and the data capture program was terminated. If the treasure was not found within 10 minutes, the participant was informed that the scavenger hunt was over and the data capture program was stopped. The participant was then requested to don the blindfold before being transported to the starting location of the next scavenger hunt.

A rest period of 40 minutes was introduced after the twelfth scavenger hunt to recharge the battery of the portable computer. After the twelfth scavenger hunt, the portable computer was docked in a recharging station, and the participant was blindfolded and transported by wheelchair to the first floor. At the end of the rest period, the participant was blindfolded again before being taken back to the fourth floor to continue with the experiment.

At the end of the scavenger hunts, the participants subjectively ranked the navigation conditions, from the most (rank=1) to least (rank=3) helpful in finding the treasure. The participant could also rank two or more conditions equally. Finally, participants were invited to provide written comments regarding their experience of the navigational tools.

### 6.3.7 Data analysis

Given the restricted access to certain hospital areas and the asymmetrical structure of the building, the navigational complexity (i.e., distance and number of wheelchair rotations) could not be strictly equal for the 24 scavenger hunts in the experiment. For this reason, we decided to use the relative energy expenditure ratio metric proposed in [172] to obtain a quantitative estimate of the physical effort exerted by the participant in each scavenger hunt. This metric is independent of navigational complexity and thus facilitated the comparison among tool conditions.

Using a two-way repeated-measures ANOVA, we tested for tool and presentation order on the relative energy expenditure ratios. In cases of significant differences, we performed pairwise one-way ANOVA tests, using a Bonferroni corrected level of significance. To check for potential spatial learning effects, we conducted regression tests of the energy versus trial number (i.e., scavenger hunt number) data for the minimap, locator and no-tool conditions.

The participants' subjective rankings of the conditions were summarized by the median statistic. Median values were normalized by their sum across all tools such that the normalized rankings across tools summed to unity. Likewise, median energy values for each tool were normalized by the sum of median energies across tools such that normalized energies also summed to unity. This normalization allowed us to present subjective and objective results side by side.

## 6.4 Results

A full statistical report for the 2-way repeated-measures ANOVA test for energy expenditure is presented in Table 6.1

As suggested by Table 6.1 and the box plot in Figure 6.3, there were significant differences in energy expenditure across tools (ANOVA, $p = 4 \times 10^{-6}$). The energy expended

Table 6.1: $E_{RATIO}$ 2-way repeated-measures ANOVA results. Dependent variables: type of navigational tool and scavenger hunt presentation order

| ***Variation Source*** | **Df** | **Sum-of-squares** | **Mean square** | **F** | **% of total variation** | **P** |
|---|---|---|---|---|---|---|
| *Interaction* | 14 | 1.84 | 0.13 | 1.68 | 12.16 | 0.07 |
| *Scavenger hunt #* | 7 | 0.46 | 0.07 | 0.84 | 3.06 | 0.55 |
| *Tools* | 2 | 4.01 | 2.01 | 50.16 | 26.45 | 4.00E-06 |
| *Subjects (matching)* | 15 | 0.6 | 0.04 | 0.51 | 3.95 | 0.93 |
| *Residual* | 105 | 8.24 | 0.08 | | | |

taking into account the scavenger hunt presentation order (i.e. scavenger hunt number) did not reveal statistical differences ($p = 0.55$), the later revealing no significant changes in energy expenditure over the different trials. Subsequent pairwise one-way ANOVA tests revealed that the baseline condition, navigating without tools, is statistically different from minimap-aided ($p = 1.3 \times 10^{-4}$) and locator-aided ($p = 1.7 \times 10^{-5}$) navigation. No statistical differences in energy expenditure were found between the two tool-aided navigation options ($p = 0.13$).

Median subjective preference rankings of the different tool alternatives are shown as hatched bars in the normalized bar graph of Figure 6.4. Lower values in the graph indicate greater user preference (higher subjective ranking) and lower estimated energy expenditure. In the subjective data, there were no cases where the participant ranked two tool conditions as equally helpful. Objective and subjective data both indicate that navigation with either the locator or the minimap is preferred over navigation without tools. Interestingly, all male participants preferred the minimap tool while all female participants fancied the locator tool. This finding echoes previous suggestions that males are allocentric navigators while females are egocentric wayfinders [104].

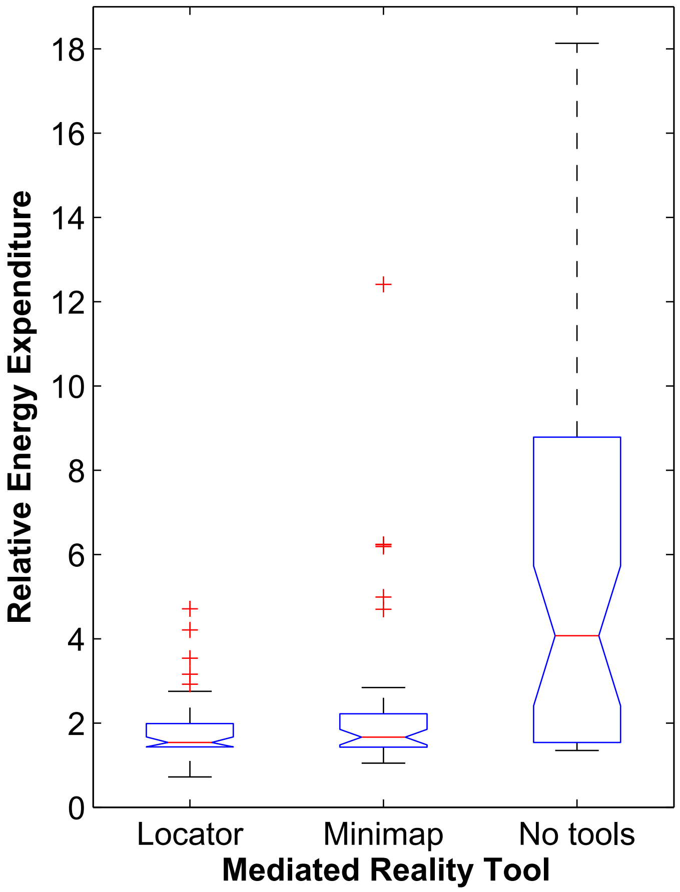

Figure 6.3: Relative energy expenditure ratio per tool. The y-axis has been cropped for visibility, occluding three outliers for the navigation with no-tools case. The relative energy expenditure ratio metric was introduced in [172].

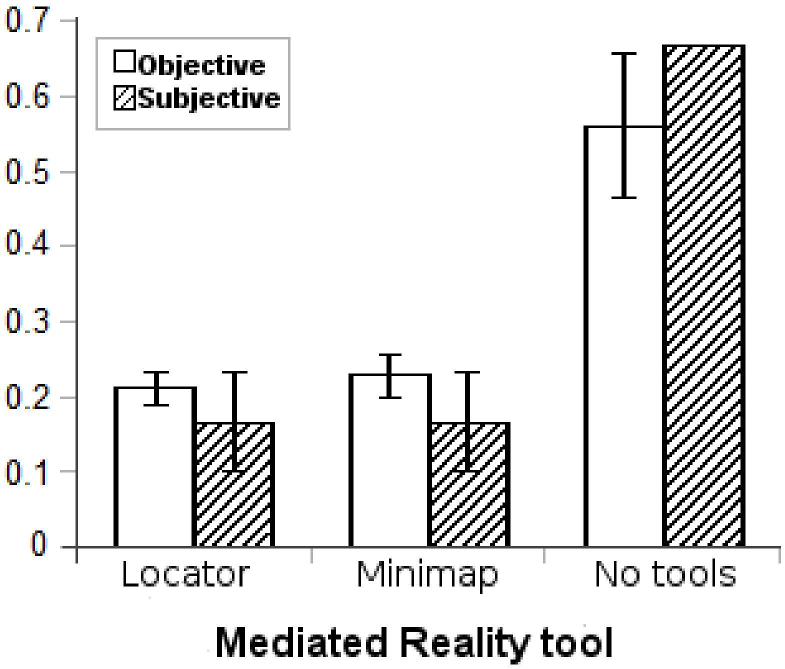

Figure 6.4: Summary of the objective and subjective tool evaluations. The vertical bars represent normalized median values for each tool. The error bars represent the quartile variation coefficient for each tool.

## 6.5 Discussion

### 6.5.1 Merits of location-based navigational assistance

The observed reduction in energy expenditure with tool usage confirms the hypothesis that both the location-based minimap and locator tools have a positive impact on navigational performance. Furthermore, the energy and subjective results reported here resonate closely with the results presented in [172], where the same tools were offered to participants during scavenger hunts in a virtual environment. This suggests that there is some ecological validity to human navigation experiments performed within virtual environments. The lack of statistical difference between tools suggests that both tools provided similar navigational benefits to the population under study in the context of an unfamiliar hospital environment. From the written subjective feedback, participants indicated that the minimap provided additional structural information about the environment which facilitated advanced planning of navigational choices. As the proposed solution is a terminal-based technique, i.e., the indoor position is estimated exclusively on the user's personal mobile device (in this case a laptop computer), the user's location privacy is maximally preserved. The MERLA system could be easily extended to deliver landmark information to the user, since key landmarks could be labeled with fiducials and added to the location database. The visual display could then provide the user with semantic location labels. Landmark-based directions are necessary for effective wayfinding via mobile devices [133].

### 6.5.2 Spatial learning effects

By blindfolding participants between scavenger hunts and by presenting multiple hunts, each with different starting and ending locations, we had attempted to mitigate spatial learning effects throughout the experiments. In other words, we endeavored to keep the participants in a transient state of topographical disorientation during the experiment.

[151] recently demonstrated that blindfolding and whole-body rotations could spatially disorient participants in a way that induced object localization errors. In the present study, the lack of change of energy expenditure over time, as revealed in the previous section, suggests that there was indeed negligible spatial learning.

### 6.5.3 Head versus body referencing

The navigational tools presented in this article are referenced to the user's upper-body orientation, as opposed to head orientation, which has been typical in other head-mounted augmented reality display studies [136, 134]. Conceivably, a head-referenced system may be more conducive to visual-spatial orientation. However, the literature on the merits of head-proprioceptive feedback during navigation are inconclusive at present [148, 149]. Furthermore, [182] discovered that under certain circumstances, body-aligned reference directions can be have a greater influence on human spatial memory than a head-aligned reference direction. More research is needed to elucidate the value of anchoring mediated reality tools for navigation to a head versus an upper body reference.

### 6.5.4 System limitations

All participants expressed difficulty in viewing the navigational tools via the head-mounted see-through display when approaching an area illuminated by direct sunlight. To improve tool visibility, participants covered the lens of the mediated reality helmet with their hand while traversing such areas. Alternative mediated reality display hardware or the addition of a photochromic lens may address this issue in the future. On occasion, the navigational tools violated the user's perceptual expectations as suggested by the following written comment, "The arrow cuts corners through walls when turning and that's confusing". This visual anomaly is likely due to drift errors inherent in the dead reckoning position estimation subsystem and should be addressed in future design iterations. Like other visual-exclusive wayfinding tools, the locator and minimap in their present form may not be conducive to the formation of cognitive maps [159]. Consequently, users may develop reduced situation-awareness and long-term tool reliance rather than build re-usable, robust spatial knowledge [115]. The addition of landmark-based directions, as suggested above, may in part alleviate this issue.

### 6.5.5 Study limitations

The metric used to quantify the effect of indoor orientation tools was based on energy expenditure. However, the participant did not actually expend energy as he or she sat in a wheelchair that was pushed by a research assistant. The metric was developed from energy expenditure measurements of real walking tasks [172] and thus approximates the energy that the user would have expended had he or she navigated by foot. Furthermore, the measure does take into account the distance traversed and the magnitude of orientational adjustments, and hence is a faithful reflection of the physical effort exerted in reaching the treasure.

For practical reasons, our experiments were conducted within a single level of the building. The impact of our mediated reality system on inter-floor navigation is yet unknown. Future experiments will include multilevel scavenger hunts. For estimating the floor on which the user is situated, the wheelchair or pedestrian dead reckoning location systems can be instrumented with a barometer. Nonetheless, our study commissioned a significantly larger navigation space than that deployed in previous studies [53].

The study only engaged a modest sample of participants, but each participant performed a relatively large number of trials. Nonetheless, the principal finding that mediated reality tools enhanced wayfinding performance persisted both within and between participants.

### 6.5.6 Future work

Following a user-centred design framework [88], future research will extend our present system to accommodate individuals with topographical disorientation. The extended system may include an audio-based augmented reality tool [133] that guides the user through a personalized optimal route, intersection by intersection, as proposed in [170]. Audio tools may be required as topographical disorientation can be associated with impairments of visual perception [31, 29]. Given that differences in wayfinding strategies between men and women have been reported [104], future research will also investigate potential gender-based preferences for wearable navigational tools. The relative merits of "on-demand" versus "continuous" location-based navigational assistance [53] also deserves further investigation.

## 6.6 Conclusion

Objective and subjective data support the conjecture that topographical orientation in an unfamiliar indoor environment can be enhanced by location-based navigational assistance offered via mediated-reality, visual tools. A user-centered design of mediated reality tools, presented through the MERLA system, may lead to the creation of assistive devices that improve the independence of people with topographical disorientation.

## 6.7 Acknowledgements

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# Chapter 7

# Contributions

The main scientific contributions of this thesis are:

1. An extensive and structured literature review of indoor localization technologies. This literature review could serve as a guideline for future research aimed to create wayfinding assistive devices.
2. The creation of an automated navigation algorithm, that can effectively reduce the navigational effort of patients with topographical disorientation. The algorithm accounts for the physical abilities of the patient, environmental barriers and dynamic building changes.
3. The introduction a novel wayfinding metric that can be used in the assessment of navigation tasks.
4. The identification of preferrred graphical navigation tools for mediated reality wayfinding guidance, taking into account different combinations of spatial knowledge, graphical presentations and reference frames.
5. The creation of two unique localization systems for indoor human tracking in real-time. The first localization system was oriented to pedestrians, while the second was implemented on a wheelchair.

6. The realization of a wearable, mediated reality location aware system for indoor navigation. This system proved to be an effective indoor navigation assistive device by reducing the physical effort required during wayfinding tasks in an unfamiliar indoor environment.

## 7.1 Publications

- Torres-Solis J and Chau T. (Accepted in preliminary form for publication in Ambient Intelligence, ISBN 978-953-7619-X-X). *A review of indoor localization technologies: towards navigational assistance for topographical disorientation.* Book chapter. Ambient Intelligence (A. Lazinica, editor), In-Tech Publishers.

- Torres-Solis J and Chau T (2007). *A flexible routing scheme for patients with topographical disorientation.* Journal of Neuroengineering and Rehabilitation, 4:44 (11 pages)

- Torres-Solis J, Guan M, Biddiss E, and Chau T. (In press) *Mediated reality tools for navigation in smart environments.* Technology and Health Care, Special Issue: Smart environments: technology to support healthcare (Invited).

- Torres-Solis J and Chau T (submitted). Wearable indoor pedestrian dead reckoning system. Pervasive and Mobile Computing, (Under review, Manuscript number: PMC-D-09-00006).

- Tores-Solis J and Chau T (submitted). *A mediated reality location aware (MERLA) system to facilitate indoor topographical orientation.* Journal of Location Based Services. Manuscript number: TLBS-2009-0016

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