

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

ARCES - ADVANCED RESEARCH CENTER ON ELECTRONIC SYSTEMS
FOR INFORMATION AND COMMUNICATION TECHNOLOGIES E. DE CASTRO

Context Detection and Abstraction In Smart Environments

Marina Pettinari

TUTOR
Professor
Tullio Salmon Cinotti

COORDINATOR
Professor
Riccardo Rovatti

PHD. THESIS
January, 2005 - December, 2007

PHD PROGRAM IN INFORMATION TECHNOLOGY

CYCLE XX - ING-INF/05

“Life is really simple, but we insist on making it complicated.”

Confucius

Keywords

Smart Environments

Cultural Heritage

Context-Aware Computing

Location-Aware Computing

Sensors

Location Detection

Visitor Guides

Table of contents

Keywords	5
Table of contents	7
Figure Index	11
Table Index	13
Abstract	15
CHAPTER 1. INTRODUCTION	17
1.1 Context-aware Computing in Smart Environments	18
1.1.1 Context Definition	18
1.1.2 Context Sensing	20
1.1.3 Context-aware Computing Systems	20
1.1.4 Location Aware Systems	21
1.2 Context Awareness in Cultural Heritage Domain	22
1.2.1 Cultural Heritage Domain	22
1.2.2 Context-aware applications in CH domain	23
1.2.3 Requirements	24
1.3 Research Context	25
1.4 Thesis contribution	26
1.5 Thesis Outline	27
CHAPTER 2. RELATED WORK IN LOCATION SYSTEMS	29
2.1 Pedestrian Location Systems Classification	29
2.2 Positioning Methods	31
2.2.1 Proximity localization	31
2.2.2 Angulation	31
2.2.3 Lateration	31
2.2.4 Pattern matching	32
2.2.5 Dead Reckoning Navigation	33
2.3 Positioning technologies	33
2.3.1 Satellites systems	34
2.3.1.1 Global positioning systems (GPS)	34
2.3.1.2 GPS improvement	35
2.3.1.3 Galileo	36
2.3.1.4 Satellite Based Navigation in Cultural Heritage Application	37
2.3.2 Cellular Based Network	38
2.3.2.1 Global System for Mobile Communication (GSM)	39
2.3.2.2 UMTS	39
2.3.3 Indoor localization Systems	40
2.3.3.1 Ultrasound localization systems	40
2.3.3.2 Infrared localization systems	41
2.3.3.3 Radio localization systems	42
2.3.3.3.1 WLAN based positioning system	43
2.3.3.3.2 Bluetooth	46
2.3.3.3.3 Zigbee	47
2.3.3.3.4 RFID	48
2.3.3.3.5 Ultra-Wide Band (UWB)	49
2.3.4 Navigation by Vision	50
2.3.5 Dead Reckoning Systems	51
2.3.5.1 Dead reckoning sensors	52
2.3.5.1.1 MEMS Gyroscope	53
2.3.5.1.2 MEMS Accelerometer	54
2.3.5.1.3 Magnetic Compass	54

2.3.5.2 Pedestrian Dead Reckoning Techniques	55
2.3.5.3 Pedestrian Dead Reckoning Platforms	56
2.5 Location information and space models	59
2.6 Abstracting location	59
2.6.1 Multi Sensor Approach	60
2.6.1.1 Location Stack	61
2.6.1.2 PlaceLab	61
2.6.2 Chosen Technologies for Integration	62
2.7 Conclusions	62
CHAPTER 3. LOCALIZATION IN SMART ENVIRONMENTS	65
3.1 Multi-Sensor Unit: the Dead Reckoning Platform	65
3.1.1 Multi-Sensor Unit: characteristics	66
3.1.1.1 Whyre	66
3.1.1.2 Improvement of Multi-Sensor Unit	68
3.1.2 Pedestrian Tracking Algorithm	71
3.1.2.1 Step detection	71
3.1.2.1.1 Algorithm	71
3.1.2.1.2 Evaluation and results	74
3.1.2.2 Step length estimation	75
3.1.2.2.1 Algorithm	75
3.1.2.2.2 Evaluation and Results	76
3.1.2.3 Heading estimation	76
3.1.2.3.1 Algorithm	76
3.1.2.3.2 Evaluation and Results	78
3.1.3 Conclusions	78
3.2 Dead reckoning supports stereo vision in pedestrian navigation	79
3.2.1 Stereo Vision based Tracking System	79
3.2.2 Pedestrian Dead Reckoning Calibration	82
3.2.2.1 Position Initialization	83
3.2.2.1.1 Algorithm	83
3.2.2.1.2 Evaluation and Results	83
3.2.2.2 Step Length Calibration	84
3.2.2.2.1 Algorithm	84
3.2.2.2.2 Evaluation and Results	86
3.2.2.3 Heading Initialization and Correction	86
3.2.2.3.1 Algorithm	86
3.2.2.3.2 Evaluation and Results	87
3.2.3 Time synchronization considerations	90
3.2.4 Multi User Identification	90
3.2.4.1 Matching between trajectories	91
3.2.4.1.1 Algorithm	91
3.2.4.1.2 Evaluation and Results	92
3.2.4.2 Pre -Identification technique	94
3.2.5 System Architecture	96
3.2.6 Conclusions	97
3.3 Dead reckoning supports GPS in pedestrian navigation	97
3.3.1 GPS Pedestrian Navigation	98
3.3.1.1 GPS Receivers and Protocols	99
3.3.1.1.1 Evaluation of GPS receivers	99
3.3.1.1.2 Validity and accuracy of GPS fix	101
3.3.2 Pedestrian Dead Reckoning Calibration	103
3.3.2.1 Position Initialization	103
3.3.2.2 Heading Initialization and Correction	105
3.3.2.3 Step Length Calibration	106
3.3.2.4 Evaluation and Results	108
3.3.3 Conclusions	109
3.4 An indoor identification and tracking system: RF and vision integration	109
3.4.1 System Overview and main system components	109
3.4.1.1 WLAN-Based Tracking and Magimap	110

3.4.1.2 Vision Tracking System _____	112
3.4.2 System Integration _____	112
3.4.2.1 Automatic detection of the entrance in the supervised room _____	113
3.4.2.2 Identification Algorithm _____	116
3.4.3 System Architecture _____	116
3.4.4 Evaluation and conclusions _____	119
3.5 Considerations _____	121
<i>CHAPTER 4. CIMAD - A Framework for context-aware applications _____</i>	<i>123</i>
4.1 Framework for context-aware applications _____	123
4.1.1 CIMAD Architecture _____	126
4.1.1.1 Context Management: MobiComp _____	126
4.1.1.2 Fedora content store and the Content Adaptation Layer _____	128
4.1.1.3 Software interfacing component _____	128
4.2 CIMAD developed services _____	129
4.2.1 Museum Management Systems _____	129
4.2.1.1 Services for the Visitor – Visitor Guide _____	129
4.2.1.2 Services for Museum Management _____	131
4.2.1.2.1 Museum Presence Monitor _____	131
4.2.1.2.2 Museum Registration Desk _____	134
4.2.1.2.3 Visitor Tracking System _____	135
4.3. Conclusions _____	135
<i>CHAPTER 5. CONCLUSIONS _____</i>	<i>137</i>
<i>PUBLICATIONS _____</i>	<i>141</i>
<i>BIBLIOGRAPHY _____</i>	<i>143</i>

Figure Index

Figure 1: Pedestrian localization system classification.....	30
Figure 2: Positioning Method Classification	30
Figure 3. Dead reckoning navigation.....	55
Figure 4: Location sensing technologies [Hazas et al.'04].....	63
Figure 5: Whyre: the device.....	66
Figure 6: Whyre: use and components.....	67
Figure 7: MSU I.....	68
Figure 8: MSU II.....	70
Figure 9: MSU II with Bluetooth connection.	70
Figure 10. MSU III	70
Figure 11: Trajectory detection algorithm	71
Figure 12: Frontal vs. vertical acceleration.....	72
Figure 13: Frontal acceleration during a step.....	72
Figure 14: Finite State Machine.....	73
Figure 15: Frontal acceleration and step detection	74
Figure 16: Leg position during a gait cycle	75
Figure 17: Heading system: conceptual schema	77
Figure 18: MSU compared with GPS	78
Figure 19: Tracking system with stereo vision	80
Figure 20: Stereo-Vision System interface	81
Figure 21: VTS-PDR Localization System.....	82
Figure 22: Position correction.....	83
Figure 23: PDRS position correction.....	84
Figure 24: PDRS and VTS steps.....	85
Figure 25: Least Square Orthogonal Distance	87
Figure 26: Direction error (1).....	88
Figure 27: Correction of PDRS direction (1).....	88
Figure 28: Direction error (2).....	89
Figure 29: Correction of PDRS direction (2).....	89
Figure 30: PDRS sampling time Figure 31: VTS sampling time	90
Figure 32: Experiment (a) Figure 33: Experiment (b).....	92
Figure 34: Difference between PDRS and VTS derivative direction (1).....	93
Figure 35: Difference between PDRS and VTS derivative direction (2).....	93
Figure 36: Recalibration area – tiles	94
Figure 37: VTS-PDRS finite state machine.....	94

Figure 38: System calibration with two users	95
Figure 39: VTS-PDRS system architecture	96
Figure 40: GPS vs. PDRS In Pompei.....	98
Figure 41: Sirf message	99
Figure 42: Real trajectory	101
Figure 43: Royaltek trajectory Figure 44: Holux trajectory	101
Figure 45: Combination of PDRS with GPS	104
Figure 46: PDR alignment	104
Figure 47: Heading correction	106
Figure 48: Step Length calibration.....	107
Figure 49: Combination of GPS with PDRS	108
Figure 50: Identification-positioning system example.....	110
Figure 51: MagicMap Overview (from Magicmap site).....	111
Figure 52: 3D Tracker Interface.....	112
Figure 53: User states.....	114
Figure 54: Detection region.	114
Figure 55: Rssi of the nearest AP in the different state of the client.	115
Figure 56: linear regression of that AP's signal.....	115
Figure 57: System Architecture	117
Figure 58: System Data Flow.....	118
Figure 59: Application Interface.....	119
Figure 60: CIMAD Context-Aware Framework.....	124
Figure 61: The Kent MobiComp infrastructure	127
Figure 62: ConteXtML	127
Figure 63: Museum Visitors Daily Statistics-1	133
Figure 64: Museum Visitors Daily Statistics-2.....	133
Figure 65: Museum Visitors Monthly Statistic.....	134

Table Index

Table 1: IMU suitable for pedestrian navigation	58
Table 2: Distance error.....	76
Table 3: Estimated α value.....	86
Table 4: Estimated distance with calibration	86
Table 5: Estimated distance without and with calibration	86
Table 6: Mean Value and STD of the difference function.....	93
Table 7: Royaltek Performances	100
Table 8: Holux Performances	100
Table 9: DOP classification	102
Table 10: Value of GPS speed when the user is stading	103
Table 11: Estimated distance with calibration	107

Abstract

Context-aware computing is currently considered the most promising approach to overcome information overload and to speed up access to relevant information and services. Context-awareness may be derived from many sources, including user profile and preferences, network information, sensor analysis; usually context-awareness relies on the ability of computing devices to interact with the physical world, i.e. with the natural and artificial objects hosted within the "environment". Ideally, context-aware applications should not be intrusive and should be able to react according to user's context, with minimum user effort.

Context is an application dependent multidimensional space and the location is an important part of it since the very beginning. Location can be used to guide applications, in providing information or functions that are most appropriate for a specific position. Hence location systems play a crucial role. There are several technologies and systems for computing location to a vary degree of accuracy and tailored for specific space model, i.e. indoors or outdoors, structured spaces or unstructured spaces.

The research challenge faced by this thesis is related to pedestrian positioning in heterogeneous environments. Particularly, the focus will be on pedestrian identification, localization, orientation and activity recognition.

This research was mainly carried out within the "mobile and ambient systems" workgroup of EPOCH, a 6FP NoE on the application of ICT to Cultural Heritage. Therefore applications in Cultural Heritage sites were the main target of the context-aware services discussed.

Cultural Heritage sites are considered significant test-beds in Context-aware computing for many reasons. For example building a smart environment in museums or in protected sites is a challenging task, because localization and tracking are usually based on technologies that are difficult to hide or harmonize within the environment. Therefore it is expected that the experience made with this research may be useful also in domains other than Cultural Heritage.

This work presents three different approaches to the pedestrian identification, positioning and tracking:

- Pedestrian navigation by means of a wearable inertial sensing platform assisted by the vision based tracking system for initial settings an real-time calibration;
- Pedestrian navigation by means of a wearable inertial sensing platform augmented with GPS measurements;
- Pedestrian identification and tracking, combining the vision based tracking system with WiFi localization.

The proposed localization systems have been mainly used to enhance Cultural Heritage applications in providing information and services depending on the user's actual context, in particular depending on the user's location.

CHAPTER 1.

INTRODUCTION

The vision of Ubiquitous computing, envisaged by Mark Weiser [Weiser'91], is closer to reality than it was in 1991. Weiser's vision anticipates a technological revolution in which the computation has a dominant role in our everyday world. This means not only that computation is embedded into the technology of everyday life, but also that we use it without thinking of them as computers but as everyday objects. The new reality of disappearing technologies into the environment has been enabled by the miniaturization of mobile devices, new possibilities offered by wireless communication, new localization techniques, falling costs, sizes and power requirements.

There are already many examples of disappearing technologies that are part of everybody life. They unwittingly interact regularly with invisible microprocessors embedded in vehicles, buildings, household appliance and entertainment systems. As reported by Weiser in [Weiser'91], "such a disappearance is a fundamental consequence not of technology, but of human psychology. Whenever people learn something sufficiently well, they cease to be aware of it".

The interaction between people and ubiquitous computing is sometimes idealized as a Smart environments, in which there is a seamless integration of people, computation, and physical reality. A key role is played by applications able to adapt their behaviour to the current context without explicit request. The context information may be retrieved in a variety of ways, such as applying sensors, network information, device status, browsing user profiles and using other sources. Several projects using context information, and more specifically location information, illustrate the idea of smart environments, in which context-aware information and services are provided to the user.

Cultural and natural heritage applications have proved to be an attractive vehicle for ubicomp researchers. Developed projects are mainly focused on data collection tools, museum or city visitor guides as a means of demonstrating various concepts including location and context awareness and smart building environments [Ryan et al.'05]. The increasing interest in cultural heritage (CH) domain depends on many reasons, namely the inherent mobility of users, a wide diversity of attractive materials for presentation, the need to provide contents without disorienting the visitor. Interaction with the visitors should be optimized according to their situations, device characteristics and preferences. It is more and more important to understand the users behaviour inside the CH site in order to improve the

provided services, that should be adaptive, as adults and children, novices and experts, disabled and able-bodied, first-time and returning visitors all arrive with different knowledge, capabilities and expectations. Eventually, services should not only be addressed to visitors but the same infrastructure should be used to manage all the tasks involved in CH Management, from data collection, to surveillance, ending with visitor experience and site management.

The research in CH should lead improved techniques for heritage conservation, community participation, evaluating the potential of ICT to enrich scholarship and expertise in dealing with material culture and to heighten public sensitivity to the universal values and particular modes of human expression embodied in our shared inheritance of CH objects, traditions, and sites.

1.1 Context-aware Computing in Smart Environments

A Smart environment is any area of interest where there are means to detect the occupants context, so that contextual information can be used to support and enhance their abilities in executing application specific actions by providing information and services tailored to their user's immediate needs [Ryan et al.'05]. Smart environments depend on communication and cooperation between numerous devices, sensor networks, servers in the fixed infrastructure and the increasing number of mobile devices carried by people. Sensors could be embedded in the environment itself, or integrated in the platform or both. They should link computer to everyday settings and commonplace tasks. The areas of interest could be both cultural like museums, archaeological site, temples, historical city centers, but also industrial heritage sites or not cultural, like intelligent rooms, smart conference rooms, smart vehicles, smart houses, etc.

1.1.1 Context Definition

Many researchers have attempted to define the meaning of context in the past decade, considering it from different points of views. From the variety of definitions that often depend on authors' subjectiveness leaks out the difficulty to find a common one.

The first conceptualization of context was provided in [Schilit et al.'94], in which the "context" was defined as location, identities of nearby people, and resources. Since then, a large number of definitions of the terms context has been proposed in the area of computer

science. Chen in [Chen et al.'00] expanded the taxonomy of Schilit, by introducing the time class, and providing its own formal definition: “Context is the set of environmental states and settings that either determines an application’s behavior or in which an application event occurs and is interesting to the user”. In [Brown'96] context is defined as location together with other information like identities of the people around the user, the time of day, season, temperature, etc. Others provide synonyms for context, using for example terms like “environment”, “situation”, “user’s environment” and “application’s environment”, like [Rodden et al.'98] that relates the context to the application’s setting.

Most recently in [Coutaz et al.'05] context “is not simply the state of a predefined environment with a fixed set of interaction resources. It is part of a process of interacting with an ever-changing environment composed of reconfigurable, migratory, distributed, and multiscale resources”

A domain specific definition of context is provided by Roffia in [Roffia et al.'05] that defines context as the combination of physical and logical coordinates, where the physical coordinate represents the current user’s position and orientation related to a space model and the logical coordinate represents the current level-of-detail explicitly requested by the user (i.e.: the user is interested in the museum, section, hall, walls or exhibit), according to the hypothesis that it is always possible to identify a hierarchy in the CH site organization.

The mentioned context definitions are only a subset of the several conceptualizations provided over last decades. They are however limited, because are not able to consider all the types of different situations. Two more general definitions of context are provided below. According to [Abowd et al.'99] context is “any information that can be used to characterize the situation of entities (i.e. whether a person, place or object) that are considered relevant to the interaction between a user and an application, including the user and the application themselves. Context is typically the location, identity and state of people, groups and computational and physical objects”. This notion of context includes any kind of information that is relevant to the interaction between the user and the application, and thus, any application defined as adaptive in traditional terms, is actually a context-aware application. In order to better specify this concept [Zimmermann et al.'07] attempts to concretize aspects that characterize the context. He argues that “Any information describing an entity’s context falls into one of five categories for context information: individuality, activity, location, time, and relations”.

This broad definition allows to define in every scenario the most suitable specialized definition of context, which is obviously needed for every practical implementation of Context-awareness.

1.1.2 Context Sensing

Context information with methods for composing and representing it are crucial parts of context-aware computing. By sensing context attributes context-enabled applications may display context information, capture it for later access, provide context-based retrieval of stored information or modify their behavior accordingly without explicit user intervention. A part of context information is obtained by capturing characteristics of the physical world, through the use of sensors. A sensor can be defined as a device that perceives a physical property and maps the value to a quantitative measurement [Goertz et al.'04].

Multiple sensors are needed for gather contextual information, because a single output of a sensor might not produce sufficient information due to uncertainty and unreliability of the sensor itself. The combination and fusion of multiple sensor output can be used to reduce these problems. As defined in [Salber et al.'99] combining multiple sensors raises the problem of fusing the information in a meaningful way. Inspired by the sensor fusion literature, two general types of sensor fusion are envisage to be used: mechanisms based on competitive sensors and mechanisms based on complementary sensors. Competitive sensors each provides equivalent information about the environment. They are used when sensors are uncertain or unreliable, because by using them simultaneously it is possible to reduce their drawbacks. Complementary sensors provide information that can be merger to form a more complete picture of the environment. Moreover, dealing with sensors sometimes it is necessary to face problems related to intrusiveness, either because of their operation or their form factor doesn't fit the natural flow of the user's activities. Location sensing methods and technologies will be presented and discussed in next chapter, highlighting the diversity of available systems.

1.1.3 Context-aware Computing Systems

Context-aware computing refers to a paradigm in which the behavior of individual components is determined by the circumstances in which they find themselves to an extent that greatly exceeds the typical system/environment interaction pattern common to most modern computing [Roman et al.'04]. Context-aware systems use context data to improve application and device capabilities; they automatically adapt themselves to discovered context, by changing the application's behavior.

Even if several definitions of context-aware computing exist, they are often application limiting and application dependent. The first researcher referred to context-aware computing was Schilit in [Schilit et al.'94], defining it as the ability of software to adapt itself to its location of use, the collection of nearby people and objects, as well as changes to those

objects over time. After that, following conceived definitions can be classified into two categories: using context and adapting to context. In [Hull et al.'97] and in [Pascoe et al.'99] context-awareness is defined as the ability of computing devices to detect and sense, interpret and respond to aspects of a user's local environment and of the computing devices themselves. On the other side, in [Salber et al.'99] context-awareness is defined from a computation point of view, in which the context is used to automate a software system, to modify an interface, and to maximize flexibility of a computational service.

Reviews of early context-aware systems can be found in [Hull et al.'97; Chen et al.'00; Korkea-Aho'00].

1.1.4 Location Aware Systems

The relevance of location information in context-awareness mechanisms for ubiquitous computing is evident from early researches [Elrod et al.'93]. Several researchers have contributed since then to the field of ubiquitous computing and localization like [Chen et al.'00]. Furthermore, recent advances in wireless communication devices, sensors, hardware technology (particularly with the Micro-Electro-Mechanical Systems - MEMS) make it possible to envision new high resolution localization systems able to accurately locate people, equipment and other objects.

Localization systems enable a connection between the physical and the virtual world [Estrin et al.'02], requiring less attention and conscious effort by users, in line with the goal of the ubiquitous computing environment. As such, context awareness, and location as part of that context, is an important factor in applications in the ubiquitous computing environment.

For many reasons determining the user location is not a trivial process. Amongst these reasons are the big difference in localizing people outdoors or indoors, the difficulty to achieve the expected accuracy and precision. Indeed while outdoor the GPS technology is widely used and it is a de fact standard thanks to its ubiquity, indoor localization is still an open research area. Alternative solutions often adopted, are based on radio signals (802.11, Bluetooth, RFID), ultrasound or infrared technology.

One of the first context-aware system based on location called Active Badge Location System was proposed in [Want et al.'92]. Using infrared technology this application is able to determine a user's current location providing services like the forwarding phone calls to a telephone close to the user. Other important context-aware applications were developed after that, like Cyber Guides [Abowd et al.'97], CoolTown [Kindberg et al.'01], etc.

Many location aware systems use a limited set of sensing technologies, that limit their reliability, because typically they can work indoor and not outdoor or vice versa. If a heterogeneous set of sensors is used it is possible to improve the accuracy by fusing the data of multiple independent sources of location information over time. A higher number of sources of location information will typically improve both the spatial coverage and the rate at which location information is available, which should increase the accuracy and precision of position calculations. For instance taking advantages of many sources of location information could solve problems related to failure of a single sensor, due to redundancy in location information.

1.2 Context Awareness in Cultural Heritage Domain

This thesis mainly deals with location aware systems in CH domain. CH represents a challenging scenario for applying context-aware technologies and building smart Environments, since it shows very demanding end-user requirements for information and communication technologies.

1.2.1 Cultural Heritage Domain

CH is becoming a greater attraction factor for tourism worldwide and many countries are aiming to offer lower-cost, but higher-quality, contents and services that can provide better visibility to their museums, sites and landscapes. A recognized problem is that visitors often do not remember what they have seen. Moreover many museums present their exhibits in a passive and non-engaging way and visitors information found does not cover the visitor's specific interests. One possibility of making exhibitions more attractive is to improve their interaction with the guide, enhancing learning experience for visitors, based on the hypothesis that the more they retain, the greater the demand for knowledge will be.

In order to overcome the issues of insufficient exposure (few visitors) and insufficient retention, CH sites need to be accessed in a much more organized way. They need to be noticed by external Cultural Tourism operators and they need to provide contents and services on site not only using dedicated guides available for rent, but also on any type of physical media desired by the user, including their own smartphone or PDA. In order to exploit its potential to interest visitors, a country should face the above mentioned issues with solutions that are deeply integrated within the territory, and such an approach should

involve institutions at various levels, from the governments and the large international tour operators, down to the local authorities, site managers, curators and the technology providers [Raffa et al.'07a].

To better exploit these and other opportunities in the CH domain, more knowledge is needed about the complex interaction between technology and the cultural sector. Exploring these relationships is the role of EPOCH (European Research Network on Excellence in Processing Cultural Heritage) [EPOCH], a four years European project, started on March 2004 and founded by the European Commission under the Community's Sixth Framework Programme (contract no. IST-2002-507382). The project involves about a hundred European partners joining their efforts to improve the quality and effectiveness of the use of information and communication technology for CH. Participants include universities departments, research centers, heritage institutions like museums or nation heritage agencies, and commercial enterprises, endeavoring together to overcome the fragmentation of current research in this field. EPOCH's primary objective is "to integrate the currently fragmented efforts in research directed toward developing intelligent IST technologies for cultural heritage and their use in sustainable Cultural Heritage applications".

1.2.2 Context-aware applications in CH domain

Context-aware computing can provide extremely meaningful insights when applied in museums or archaeological sites, both for first time visitors and for specialists. In this types of environments visitors often need to be aware not only of location, but also of social, political, cultural, historical, economic and scientific related aspects in order to better approach and appreciate the exposed object.

Mobile devices are considered one of the enabling technology, because they can enable not only the visitor but also the museum staff and the curators to get the best out of their use in the museum setting. As multimedia visitor guides, they need to help museum visitors find their way through an exhibition, provide to visitor the right information at the right time. Exploitable advantages of mobile guides are reported in [Damala et al.'07].

Several context-aware applications in CH domain have been developed. One of the first is Archeoguide [Vlahakis et al.'01], proposed by a European Project of the 4th Framework Program a decade ago. It is a wearable augmented reality system for personalized tours in CH, based on head mounted displays. Since then, many challenging mobile CH applications have been considered, addressing the interests of visitors, researchers and operators. The vast amount of work performed in this field ranges from location and orientation to automatic detection of user profiles and preferences. Spasojevic

and Kindberg in [Spasojevic et al.'01] describe experiences from the CoolTown project by HP, investigating how a web-based computing infrastructure can provide museum visitors with an augmented experience. This project is based on the design of a study of users equipped with devices gathering context data from RFID, barcode and radio beacons.

The attention of researchers is focused also on context-dependant data collection, a crucial aspect of CH research, providing accurate documentation to preserve and make knowledge accessible. In [Nick et al.'99] is shown how a sensor-enhanced handheld device can be used in research field survey. It leverages inexpensive sensors, such as GPS, in conjunction with an embedded custom-made GIS to contextualize field data. During a two-year experiment it was shown that such a system can be more effective than paper-based methods to collect data on-site. Similar work involving on-site recording during an excavation is described in [Ancona et al.'99].

A relevant aspect to be considered is to not limit the CH applications to a single specific device. There is the need to deliver contents and services on heterogeneous devices, i.e. desktop PCs, notebooks, mobile phones, PDAs, Web TVs and dedicated appliances. This approach envisages the development of generic applications that dynamically adapt to the device characteristics and communication channel. For example, multi-channel applications can be used in a scenario where the same content needs to be offered to kiosks located in each exhibition room and also to sensor-enabled PDAs, adapting in real-time the content to the device characteristics and to the user's context. [Garzotto et al.'03]

The referred examples demonstrate the effort of researchers to develop context-aware system in CH domain.

1.2.3 Requirements

Considering the above mentioned applications it is noteworthy that ubiquitous systems in CH domain are subject to more strict issues, with respect for instance to smart offices or smart houses. Building a smart environment in museums or in protected sites is a challenging task because localization and tracking are usually based on technologies that are difficult to hide or harmonize within the environment. For example in many cases visible tags displaying bar or number to be keying in, or showing references to electronic tags (such as radio frequency identification tags or infrared emitters) are not a good solution to apply to solve the localization problem. They might be obtrusive, requiring additional space, and incompatible with the exhibition concept [Bruns et al.'07]. Furthermore, the exhibition layout can be changed, and the installed infrastructures can not match new requirements.

Another problem is related to the fact that a lot of museums and archeological sites have large complex environments both indoor and outdoor. So it is not possible to use a unique sensor, seeing that context-aware application must yield a precise localization, even in situations in which for example GPS cannot provide navigational information, including indoor locations and narrow streets. In addition technologies used for indoor localization like active badges or beacon frequently require installation of support infrastructures. Moreover they are subject to intrinsic errors that require both offline and online calibration phase. As a result all these drawbacks involve substantial effort and expense from a research point in order to find alternative localization solutions less intrusive and more efficacy. In general developed solutions should not be restricted to an individual museum or visitor site, but the big effort should conduct in creating a more general application that can be reused in different CH sites.

1.3 Research Context

The research reported in this thesis is rooted mainly in the EPOCH Project [EPOCH]. It involved the development of a framework called CIMAD (standing for “*Common Infrastructure/Context Influenced Mobile Acquisition and Delivery of cultural heritage data*”). The CIMAD project is a collaboration between institutes from Italy (University of Bologna, University of Milan, Ducati Sistemi, IBC) and the United Kingdom (University of Kent). It is meant to seamlessly support heterogeneous device types with different form factors and usage models, i.e. custom, dedicated devices hired on site, versus privately owned PDAs and smart phones, and different location technologies, i.e. WiFi based versus GPS based. Even if necessarily incomplete and preliminary in many respects, CIMAD is aiming to speed up and simplify the development process of CH applications by providing a common framework aimed at developers and field experts with limited IT knowledge. CIMAD intends also to anticipate a future application development scenario, supporting the integration of services applicable to many CH environments. In order to provide such services, CIMAD builds on top of two infrastructure components supported by EPOCH: a context management system called MobiComp, and a content management system built on top of the Fedora digital repository. Based on a modular and re-usable context infrastructure, CIMAD aims to introduce the modularity concept to the area of CH applications, allowing overlapping functionalities and context elements to be re-used. A detailed description of CIMAD will be provided in Chapter 4.

A work in progress demonstration of CIMAD services, named “Smart Museums, Sites and Landscapes – From Visitor Guides to Collection Monitoring” was setup during the

“Interactive Salon” event organized by EPOCH held in Stockholm, Budapest, Prague and Brighton.

1.4 Thesis contribution

The effectiveness of CH information access and presentation can be increased by the knowledge of the user’s context, especially user’s location, the large element of context also recognized in the literature of ubiquitous computing.

The purpose of this research was to address the lack of a single system to support the current and increasing needs of location identification in smart environments. Experiments in museums and archeological areas show that stand-alone localization systems, i.e. Global Positioning System (GPS) or Wireless Lan (WLAN) based localizations techniques, may meet the user needs in case when no strict constraint on resolution and precision are required. When a high density of artifacts needs to be located, or a high resolution is required, alternative solutions should be studied, like for example the use of dead reckoning system embedded in a wearable platform, or the exploitation of cameras able to detect and track people inside the CH environment. There is no location identification system that is able to provide precision in location identification which caters to both outdoor and indoor environment. Limits related to the use of a single technology, highlight the need to combine between them these different approaches, in order to overcome with one the limits of the other. Localization system should reach the best compromise of cost, intrusiveness, resolution and coverage. The resolution can be variable, because, especially in CH domain, it is not required to have high degree of accuracy in all the site.

The aim of this thesis is to provide a continuous infrastructure-less indoor/outdoor localization system for “difficult” environments, exploiting the co-operation between complementary systems. Developed systems are based on the smart integration of different available positioning technologies to increase the precision of the overall system. It is notable that integrating different technologies will increase their power manifold.

Different pedestrian navigation system have been developed during this research. Two solutions have been proposed to increase the accuracy and reliability of a wearable inertial sensing platform (section 3.1), both in indoor and outdoor environments.

The pedestrian indoor tracking system is based on the combination of the wearable inertial sensing platform with the stereo vision tracking system, developed by Computer Vision Lab in University of Bologna (section 3.2.1) to correct errors in position and direction accumulated by the dead reckoning. Experimental results prove the feasibility of this approach, revealing that the combination with the stereo vision tracking system improves the

accuracy by enabling the real-time calibration of the sensing platform (section 3.2.2). Further improvements are required in order to provide a reliable multi-user identification (section 3.2.3).

In outdoor environment the dead reckoning parameters are combined using GPS measurements (section 3.3). The proposed approach is based on a smart switching system, that uses accurate GPS data to continuously calibrate inertial information. This approach is however less accurate if compared with the previous one, due to the intrinsic characteristics of the GPS. For example, in some conditions like urban canyon, can have difficulties in computing position and so in providing starting position and heading and calibrating to the wearable platform.

This thesis proposes also an indoor pedestrian identification and tracking system that combines a 3D video tracking system [Ferrer-Biosca et al.'07], with a WiFi localization application (section 3.5). It is a multi resolution system, able to locate the user with high degree of accuracy in rooms equipped with cameras and with a lower degree of accuracy in area where only WiFi localization system is available. This approach aims to demonstrate how radio localization, exploiting the signal of a known Access Point, can be used to univocal identify a mobile user tracked by the vision based system. The prototype implementation shows that, while the identification of a single user is accurate, the system fails when more than one user needs to be identified simultaneously. The poor accuracy achievable with WiFi localization approach suggests to use an alternative technology to implement such an identification system, like for example a short range RFID.

A prototype application has been developed for every proposed combined system.

1.5 Thesis Outline

The thesis is organized as follow. In chapter 2 positioning technologies and methodologies approaches to detect user position are presented and discussed.

Chapter 3 illustrates solutions adopted to provide a continuous indoor and outdoor user tracking based on the combination of different technologies.

Chapter 4 describes CIMAD, the framework developed in EPOCH project, focusing on the importance of localization information, that is used to provide services to visitors and CH site.

Chapter 5 summarizes and concludes this thesis. The main contributions of this thesis are described.

CHAPTER 2.

RELATED WORK IN LOCATION SYSTEMS

The ubiquitous computing research has increased the interest in localization systems, being the user's position one of the principal context attribute required by context-aware systems. Location systems make use of sensors to measure the physical properties of the environment and then perform algorithms to compute locations.

User's location is the key aspect of a broad range of applications, such as context-aware visitor guides [Mei-Hsuan et al.'06], integrated navigation systems for firefighting [Matos et al.'06], indoor walk guide systems for blind or visually impaired [Murai et al.'07], location based systems that use wearable sensors [Foxlin'05] and public safety services such as E911 [Warrior et al.'03]. These examples are representative of the wide variety and large number of location systems available today. Pervasive applications that exploit only location information of a mobile individual (or sometimes groups of individuals) to deliver services, fall under the term Location-based service (LBS). Also CH domain has demonstrated its interest in LBS, organizing the first EPOCH workshop called "The Integration of Location Based Services in Tourism and Cultural Heritage" in Brussels, Belgium on November 21, 2006. The workshop focused on the use "of LBS, such as GPS and position detection on mobile phones or wireless LAN in both indoor and outdoor use, in tourism and cultural heritage interpretation from the point of integration, workflow, feasibility, sustainability and supporting policies".

The aim of this chapter is to document a review of pedestrian positioning technology related literature with emphasis placed upon unobtrusive positioning systems to perform precise localization. The proposed outcome is the general understanding of the potential, limitations and strengths of some of the current positioning technologies and methodologies.

2.1 Pedestrian Location Systems Classification

Technologies, methods and reference systems define the characteristics of a localization system. There are many ways to architect pedestrian location systems based on different methods and technologies. For example the same technology can be used to design localization systems characterized by different degree of accuracy, because different methods are used, i.e. the WiFi localization can use different methods, like proximity, fingerprinting,....

Pedestrian location systems can be classified with respect to different criteria. In this thesis a classification of the more relevant localization technologies is proposed, based on the distinction between Dead Reckoning (DR) and not DR approach (Figure 1).

DR systems can be broadly divided by considering the type of sensors used: fully inertial, if only inertial sensors (accelerometer and gyroscope) are used or mixed if both inertial and absolute sensors (compass) are included .

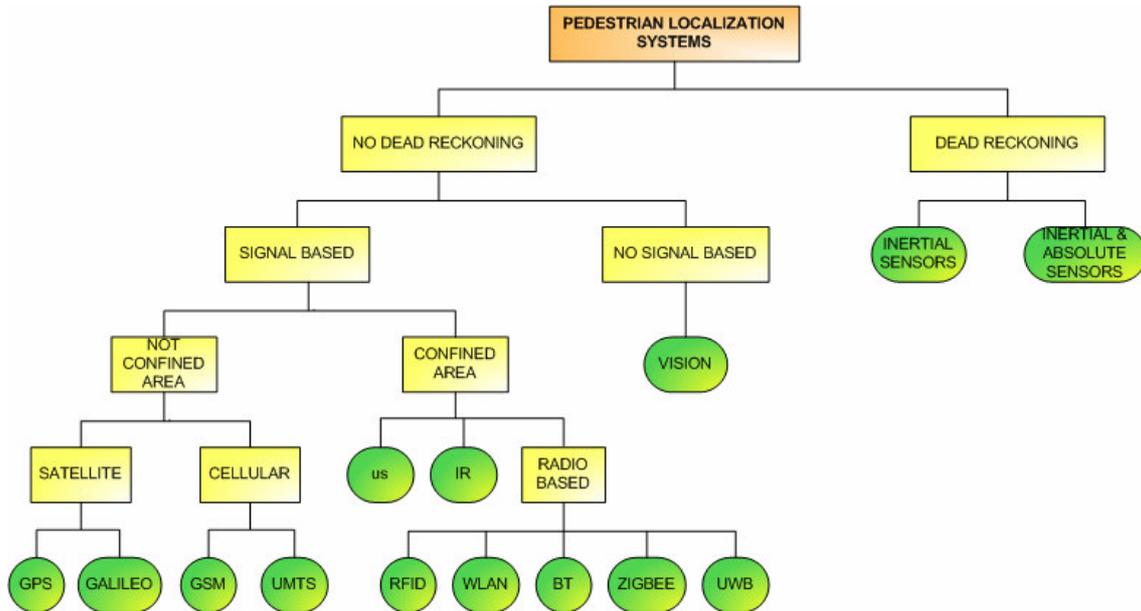


Figure 1: Pedestrian localization system classification

Not DR systems instead can be signal based, if they use signals to localize the users, or not signal based, like for example those based on vision.

Section 2.2 will describe localization methods, while all the pedestrian positioning technologies shown in Figure 1 will be described in section 2.3.

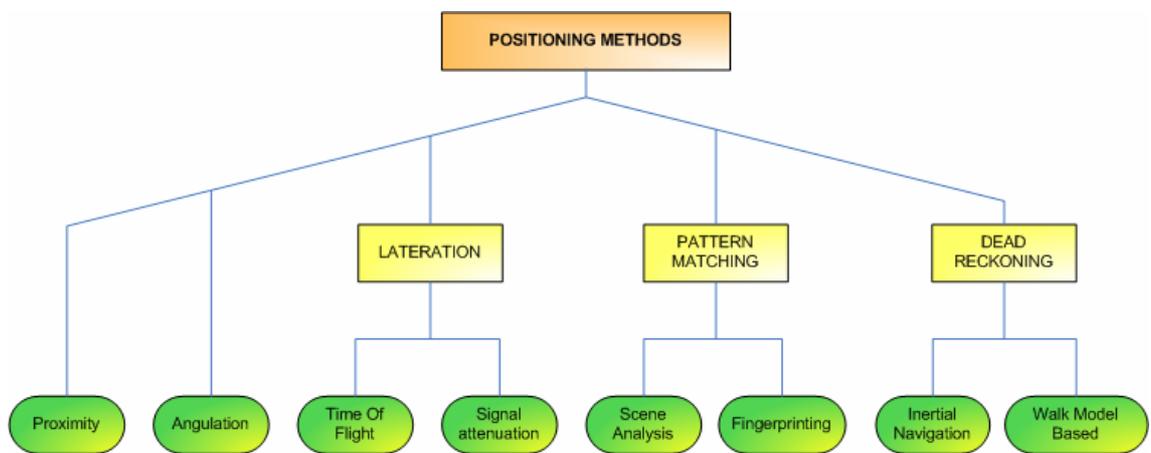


Figure 2: Positioning Method Classification

2.2 Positioning Methods

The aim of this section is to provide the basic of positioning methods used in pedestrian localization (Figure 2).

2.2.1 Proximity localization

The easiest and most intuitive type of location technique is called proximity localization. It is a widespread method because it detects when the mobile entity is inside the coverage range of radio, ultrasound or infrared signals. It can be implemented in several ways, via physical contact or wirelessly.

In cellular systems, proximity sensing is known by the terms Cell-ID, Cell of Origin (CoO) or Cell Global Identity (CGI). It has become very popular, because it requires very few modification to the infrastructure. It may be realized as terminal-based positioning, where the terminal listens to the signals sent by nearby stations, or by introducing the base station (BS) coordinates in the broadcast messages. Proximity sensing is also the principle used for the quasi totality of RFID localization systems. It has been used in indoor systems such as Active Badge.

Despite this technique offers certain advantages, such as quick location and easy deployment, it lacks in precision. In indoor systems the overall accuracy can be increased, due to the limited coverage range of the technologies used.

2.2.2 Angulation

The angulation is a geometric technique that involves the measurement of a signal approaching different receivers at known position. In 2D space two angle and one distance measurement define uniquely a location and in 3D two angle measurements, one distance and one azimuth measurement are required. Angulation is also know as angle of arrival (AoA). It requires an antenna array, or several ultrasound receiver to determine the direction where the signal originates from. The drawback of this method is that under multipath conditions, which is in general the case, the reflected signals interfere with the line of sight signal.

2.2.3 Lateration

Lateration computes the position of an object by measuring its distance from multiple reference positions; for example 2D position can be estimated using three non-collinear reference points while 3D position can be obtained from four non-coplanar reference points. Lateration technique includes two general approaches:

- “*time-of-flight*” measurement of a signal from a transmitter to a receiver. This approach opens up a number of timing and clock synchronization questions that systems employing this approach have to address. The measurement of the “time-of-flight” of a signal can be implemented in different ways:
 - Time of arrival (ToA) is based on the measurement of the time that a signal needs to travel from the BS to the mobile station (MS). This technique was studied in literature for GPS and UWB localization.
 - Time difference of arrival (TDoA) is a hyperbolic position determination technique. Three or more receiver sites measure the TDoA of a signal sent from the emitter. The possible solutions where the time difference is constant lie on a hyperbola. An unambiguous position solution can be obtained using at least two hyperbolas, i.e. three receivers are necessary. This technique is used for example in the LORAN-C Loran C Navigation System.
 - Enhanced observed time difference (E-OTD) is a technique in which the MS and two or more BSs with a known position measure the difference in the time of arrival of signals. The time difference, and therefore the distance, between the BS and the MS is then determined by correlating the two received signals. The distance still contains the clock error of the MS. Performing this operation three times for different BS solves the clock error and fixes the position of the MS. This technique requires upgrades in the handset. E-OTD is one of several technologies that carriers can deploy to meet E-911 requirements.
- “attenuation” measurement signal strength relative to its original intensity. For several types of signals a mathematical model describing the expected decrease in signal strength given the distance exists and can be used to estimate location relative to the source of the signal.

2.2.4 Pattern matching

Pattern matching, also known as scene analysis, uses features of a scene observed from a particular point to compute the location of the object. Observed features are looked up in a predefined dataset that maps them to object locations (static scene analysis). In contrast, differential scene analysis tracks the difference between successive scenes to estimate location. Differences in the scenes will correspond to movements of the observer.

Typically pattern matching is used with images frame detected by vision sensors (cameras). Vision algorithms however suffer from occlusions in the environment and are strongly conditioned by the process calibration. Furthermore, they are computationally demanding and this can limit their scalability and suitability in many applications.

The fingerprinting technique is a more novel approach based on this idea. The development of a fingerprinting based positioning system is divided in two phases: the offline and the online phase. During the offline phase, the dataset of the fingerprinting is built through a survey of the site in which the localization will be performed. During the online phase, the vector of fingerprint, provided by a mobile equipment are used to estimate position. Most common algorithms used to compare the detect signals strength with the stored signals are those based on Euclidean and K Nearest Neighbors (KNN).

The advantage of scene analysis is that the location of objects can be inferred using passive observation and features that do not correspond to geometric angles or distances. Disadvantages include the fact that the observer needs to have access to the features of the environment against which it will compare its observed scenes. Furthermore, changes to the environment in a way that alters the perceived features of the scenes may necessitate reconstruction of the predefined dataset or retrieval of an entirely new dataset.

2.2.5 Dead Reckoning Navigation

Dead reckoning (DR) navigation is one of the earliest and largely approach used in positioning systems [King'98], used first by sailors. This method determines the actual position by projecting the past heading and speed from a known past position. DR navigation requires to know the starting point of the user in order to compute the new position.

Pedestrian DR navigation includes two different approaches. The first one is the well know Inertial Navigation System (INS), that processes the inertial measurements through a double integration of accelerations to compute the navigation solution. The second approach consists in to totally avoiding integration of measurements, but rather make use of walk dynamics contained in the accelerometer signals such as frequency, maximum/minimum amplitude.

Pedestrian DR navigation represents a completely portable system that is relatively small, lightweight, low powered and accurate, allowing sub-centimeter position determination. This method can be successfully used for a real-time tracking of the mobile device.

2.3 Positioning technologies

Several types of localization systems have been developed in last decade of research.

Positioning technologies differ in their capacity to identify. Some technologies work well outdoors, while others are tailor-made for the in-building environment. The level of accuracy, granularity, intrusiveness and cost depend on the positioning systems used to locate the user.

2.3.1 Satellites systems

Satellite navigation is a signal based not confined system. It started at the end of 1970. The most important satellite system is the Global Navigation Satellite System (GNSS). There are two forms of GNSS navigation systems: the GPS and the Russian equivalent named the Global Navigation Satellite System (GLONASS). In this thesis we deal only with the first one.

2.3.1.1 Global positioning systems (GPS)

Largely considered to be the most accurate long-range location-based technology (and certainly the best-known) [Kaplan'96; Dana], the NAVSTAR GPS is a satellite navigation system developed as a US Department of Defense joint program in 1973, becoming fully operational in 1995. The GPS constellation consists of 24 solar-powered satellites (including three spare satellites) that orbit the earth in 12 hours. They are equally spaced (60° apart) on six circular orbits about 20,183 km above the earth's surface, and inclined at about 55° with respect to the equatorial plane. Each satellite transmits navigation and range data simultaneously on two frequencies, L1 (1575.42 MHz) and L2 (1227.60 MHz). Application with civilian scope can decode only the L1 frequency. The strength of the transmitted GPS signals is very low (*from -130 to -136 dBmW*) and it is susceptible to interference. Spread spectrum techniques are used by satellite transmitters to reduce the effects of noise and improve signal to noise ratio without increasing the transmitter power.

A worldwide ground control/monitoring network monitors the health and status of the satellites. GPS can provide service to an unlimited number of users, since the receivers work in a passive way. Each satellite transmits a signal comprising its identification code, a GPS time stamp, and location information (including almanac data).

The localization principle used in the GPS is the one-way TOA ranging [Feuerstein et al.'89]. The distance between the user and a satellite is measured in terms of transit time of the signal from the satellite to the user. The transmission times are imprinted upon the signals in accordance with nearly perfect and nearly perfectly synchronized atomic clocks carried aboard the satellites. The precise estimation of the arrival times is made possible by transmitting spread spectrum signals, which have wide bandwidths but each satellite can transmit its unique signal on the common frequency band.

In order to measure the true transit time of a signal from a satellite to a receiver, clearly, the clocks in the satellite and the receiver must be kept synchronized. Fortunately, this onerous requirement is easily sidestepped, allowing use of inexpensive quartz oscillators in the receivers. A user needs a minimum of four satellites in view to estimate his four-dimensional position: three coordinates of spatial position, plus time. In addition to a three-dimensional position

estimate, a Navstar receiver can calculate its velocity and heading, along with the time of day and the date.

2.3.1.2 GPS improvement

Several problems afflict GPS technology particularly in urban geographic environments where no signals can be received due to the lack of LoS requirements of at least four satellites. Furthermore, it takes a GPS receiver from the “cold” start (that is, without any knowledge about the state of the GPS constellation), up to several minutes to achieve the location fix. For these reasons a number of techniques have been studied to improve GPS accuracy, relying on external information being integrated into the calculation process. The most important are the Differential GPS (DGPS), Assisted GPS (AGPS), Wide Area Augmentation System (WAAS), and Real-time Kinematic (RTK).

Differential GPS (DGPS)

DGPS is a method used to increase integrity and accuracy GPS by using land-based references to remove the common errors. DGPS uses two receivers, the mobile device at an unknown location (to be determined), and a BS at a known, fixed location. The BS computes the error, which is characteristic for a large region around the station, and radio transmits it to Mobile device that take into account the error by correcting the current position. DGPS is based on the principle that receivers in the same vicinity will simultaneously experience common errors on a particular satellite ranging signal.

Assisted GPS (A-GPS)

A-GPS [Syrj arinne'01] systems are used to overcome the delay problems, accelerating the process of location determination and reducing it to only a few seconds, with the minimum impact on the network infrastructure. It has been pushed mainly in response to the requirement to support the E911 (US) and E112 (European) initiatives to provide location information to dispatchers handling emergency calls. This technique, using its own GPS receiver, as well as an estimation of the mobile’s location down to cell/sector, can predict with great accuracy the GPS signal the handset will receive and convey that information to the mobile. Assisted GPS is capable of providing the required accuracy - between 5-10m. At the moment different smart phones integrate the A-GPS technology.

Several commercial AGPS solutions that can be used with UMTS have been produced like gpsOne by Snaptrack or IndoorGPS by Global locate.

Although in both DGPS and A-GPS technologies satellite signal measurements are enhanced using information from terrestrial infrastructure they are substantially different. Indeed DGPS increases the location accuracy of conventional GPS, but does not increase the sensitivity of GPS receivers. A-GPS improves the performance of conventional GPS receivers

in low-SNR conditions, and can be combined with DGPS to increase the geolocation accuracy as well [Djuknic et al.'01].

Satellite Based Augmentation System

WAAS, EGNOS, and MSAS are called Satellite Based Augmentation Systems (SBAS). These systems support a satellite differential correction, whereby the correction signals that improve the accuracy of the GPS receivers are transmitted by satellite. The WAAS (Wide Area Augmentation System) is available in America, EGNOS (European Geostationary Navigation Overlay System) is the European equivalent, while MSAM (Multi-functional Satellite Augmentation System) operates in Asia, particularly in Japan. The systems send their correctional signals at the same frequencies as GPS. Since a modern 12 channel GPS maximally receives signals from 10 satellites, one channel remains free for the reception of correctional signals. The use of the corrected data is of charge free for the GPS receivers.

EGNOS consists of three geostationary satellites and a network of ground stations. It achieves its aim by transmitting a signal containing information on the reliability and accuracy of the positioning signals sent out by GPS. It allows users in Europe and beyond to determine their position to within 2 meters, compared with about 20 meters for GPS alone. EGNOS is a joint project of the European Space Agency (ESA), the European Commission (EC) and Eurocontrol, the European Organisation for the Safety of Air Navigation. It is Europe's first activity in the field of GNSS and is a precursor to Galileo, the full global satellite navigation system under development in Europe.

Real-time Kinematic (RTK)

RTK is also known as Carrier-Phase enhancement (CPGPS). It is based on the analysis of the carrier phase of GPS satellite signals rather than the usual pseudorandom signal. Standard GPS receiver determines its position by comparing the satellite's pseudorandom signal to its own internal copy, determining the delay time and deriving the distance from the satellite. In RTK the receiver examines a satellite's carrier signal rather than the pseudorandom signal.

Carrier phase measurements are extremely precise. The drawback of this technology is that it requires a specific GPS receiver with a high sensitivity [Richard'98].

2.3.1.3 Galileo

Galileo satellite radio navigation system is a joint non-military initiative of the European Union and the European Space Agency (ESA). Galileo is based on the same technology as GPS and aims to provide a higher degree of precision, thanks to the structure of the constellation of satellites and the ground-based control and management systems planned, assuring also complementarily with the current GPS system

Galileo will consist of a constellation of 30 satellites in Medium Earth Orbit (MEO) that are disposed in 3 orbital planes inclined at 54° and at an altitude of around 23,000 km. The constellation will be managed by a world wide network of ground stations. Even if Galileo is a non-military application, it incorporates all the necessary protective security features.

Two different types of receiver will be developed: mono frequency economic receiver and precise hybrid receiver that will combine Galileo with GPS signals. EGNOS program will be integrated in the Galileo system, allowing to improving the performance.

GALILEO is more reliable as it includes a signal “integrity message” informing the user immediately of any errors. In addition, it will be possible to receive GALILEO in towns and in regions located in extreme latitudes. Therefore, it represents a real public service and, as such, guarantees continuity of service provision for specific applications [GALILEO].

2.3.1.4 Satellite Based Navigation in Cultural Heritage Application

The GPS based navigation allows for fairly accurate geographical positioning and tracking through the use of GPS receivers. Thanks to technological advances, GPS receivers have become smaller and cheaper, enabling the integration of them into consumer products: onboard navigation, small computers, cell phones, personal digital assistants (PDAs) and likewise devices. The combination of performance gains and massive price reduction are the major driving force behind the successful development of new applications and large scale use by the public. A lot of applications based on GPS technology have been developed.

One of the first context-aware applications is Cyberguide [Abowd et al.'97]. It is a mobile context-aware tour guide that provides simple schematic black and white maps and information services about predefined indoor and outdoor environment. All maps and other information are static and stored on the mobile device. While indoor positioning relies on infrared beacons, the outdoor positioning is provided by GPS receiver connected to the handheld device. The system takes in account the position of the user and what he is currently looking at, with the assumption that the user is looking in his walking direction. Location is provided in textual and graphical modalities. The proposed approach is a costly system, because the indoor localization requires a large number of beacons.

The LoL@ (local location assistant) system [Pospischil et al.'02] is a mobile tourist guide for the city of Vienna developed at the Forschungszentrum Telekommunikation Wien. It has been designed for the Universal Mobile Telecommunications System (UMTS). LoL@ can dynamically generate maps and annotate them with labels and icons; it also provides basic means to interact with the map e.g. zooming and panning. The user's location is determined

using a hybrid approach: through GPS when available or through cellular phones using the Cell-ID method. An interactive location refinement procedure helps to improve location accuracy, especially in small “street canyons” where GPS reception is poor because there are not enough satellites visible.

A recent PDA based tourist guide that uses in GPS system is Arianna [Foresti et al.'06]. Arianna is a mobile handheld context-aware tour guide for art cities. Arianna is a very simple tourist guide that has two major functions: either it can be seen as a descriptive tool suitable for obtaining and searching information within multimedia components, or as a dynamic map viewer. The first set of features is achieved via interactive audio and video contents, by activating them when users need particular information about places or monuments. The second set of features allow for dynamic interacting with maps: users can perform searches to find the position of a given address, highlight points of interest on the map and their actual position automatically be uploaded through GPS. Maps are used for showing itinerary as well, by tracing paths which can be either predefined or personalized. They are using only existing technology trying to keep costs as low as possible and spending quite a lot of energy in adapting the product to user requirements.

GPS has been widely exploited in CH domain not only to develop visitor guide, but also to enable rapid data collection. For example FieldMap [Van Leusen et al.'01] has been developed specifically to suit the needs of scientific data collection in the field. It is a simple handheld GIS that, using location data typically originates from a GPS receiver, captures and shares archaeological and other data in the field associating the right position.

2.3.2 Cellular Based Network

Improvements in techniques and equipments together with public requirement for safety enhanced 911 emergency calling systems lead the development of localization systems based on terrestrial networks, namely GSM and UMTS. Accuracy required by the FCC rule for E911 calls is roughly 125 meters.

The great interest in GSM localization is supported by different advantages [Otsason et al.'05], like its pervasiveness, the wide acceptance of cellular phones and its robustness, considering that a cellular-based localization system would still work in situations where a building’s electrical infrastructure has failed. Different techniques can be used to determine user position through GSM technology, detailed in the next section. Also UMTS, is one of the Third Generation (3G) mobile systems thank to advanced features includes the support of location services.

2.3.2.1 Global System for Mobile Communication (GSM)

GSM is considered the cellular telephony standard in the world [Eberspacher et al.'01]. Today half the population in the world has its own mobile phone. These aspects pushed researchers to study this technology in depth, also because mobile phones have different advantages like ubiquitous connectivity, established interface metaphors, wide adoption. Furthermore, if compared to other localization technologies, like for instance WiFi localization, GSM is not subjected to interference, works in critical power conditions, and provides a network coverage greater than those provided by WiFi networks [Varshavsky et al.'05].

First localization techniques based on GSM networks appeared in Japan and USA during 2000. The study of this kind of localization was driven by the E-911 requirements for emergency location.

Different approaches can be used to locate mobile users using GSM signals. The simpler one is the Cell-ID [Zhao'02] that relies on the fact that mobile networks can identify the approximate position of a mobile handset by knowing which cell the device is using at a given time. The Cell-ID accuracy depends on cell size - at best 150m in a "pico cell" (i.e. urban places), to over 30km in rural environments. Further, it requires knowledge of the location of the base stations. The major drawback is that the telephone operator has full control over the services and users cannot have access to the network back end without their permission. To overcome these limitations, the fingerprinting technique can be applied. Contrary to the Cell-ID approach, fingerprinting requires a training phase. The use of fingerprinting in GSM localization has been applied in server-side, wide-area positioning [Laitinen et al.'01], indoor positioning (including floor estimation) [Otsason et al.'05], and outdoor positioning [Chen et al.'06].

More complex techniques include time based methods i.e. TOA, TDOA, AOA. Both TOA and AOA positioning techniques make use of trilateration methods which require at least three BSs. A solution requiring less than three BSs has been proposed in [Porretta et al.'04].

GSM localization is an example of both outdoor and indoor tracking system. Even if some efforts have been done to improve its accuracy, the achieved resolutions are still low to be used as localization technology in museum multimedia guides.

2.3.2.2 UMTS

UMTS is one of the Third Generation (3G) mobile systems being developed within the ITU's IMT-2000 framework. Advanced features of UMTS networks include the support of location services, to allow the development of new and innovative LBSs. Localization techniques specified in the 3GPP (Third-Generation Partnership Project) to localize MS in

UMTS networks are similar to those defined for GSM. It comprises a fully network-based Cell ID (section 2.3.2.1), and a time-biased OTDOA-IPDL.

The Observed Time Difference of Arrival With Idle Period Downlink (OTDoA-IPDL) is the UMTS counterpart of E-OTD and follows the same principles, that is, terminal-based lateration. Timing measurements at the terminal suffer from the so-called hearability problem, that needs a periodically interruption of downlink transmissions during the measurements [Kupper].

A more detailed overview of cellular localization systems based on UMTS network is provided in [Borkowski et al.'06]

2.3.3 Indoor localization Systems

In contrast to the aforementioned technologies, like satellite and cellular, that identify the user's location in open areas, indoor positioning technologies have limited coverage range, such as a building or any other confined spatial area. Typically they are considered indoor, because deploying them into a wide area is either cost prohibitive or not technically possible, i.e. infrared localization which is perturbed by infrared interference from the sun.

Typically indoor technologies are dependent on a set of technologies used for transmitting wireless data in closed environments, such as infrared, ultrasound and Bluetooth systems. Depending on the mechanisms and techniques, considerable costs arise for the stationary and mobile devices. *“An ideal location sensor for use in indoor environments would possess several important properties. Not only would it provide fine-grain spatial information at a high update rate, but would it also be unobtrusive, cheap, scalable and robust”* [Harter et al.'99].

2.3.3.1 Ultrasound localization systems

Ultrasound (US) based tracking systems are implemented using the time-of-flight lateration technique. They are based on the principle of trilateration and uses multiple emitters and sensors to obtain a set of time intervals from which the precise position is calculated.

The first US based localization systems was the *Active Bat* [Harter et al.'99] developed by AT&T researchers. Users and objects to be localized carry small battery powered tags (called Bat). When the controller sends a request via a short-range radio, the Bat responses with an ultrasonic pulse received by a wired network of ceiling-mounted sensors disposed as a grid. At the same time the controller sends the radio frequency request packet, it also sends a synchronized reset signal to the ceiling sensors. Each ceiling sensor measures the time interval

from reset to ultrasonic pulse arrival and computes its distance to the Bat. The local controller then forwards the distance measurements to a central controller, which performs the lateration computation. The research reports that 95% of readings are within 9 cm of their true positions. It can also compute orientation information given predefined knowledge about the placement of Bats on the rigid form of an object and allowing for the ease with which US is obstructed. One of the problems with Active Bat is that, even if accurate, it requires a vast amount of infrastructure. Receivers need to be placed in a square grid and connected by a network of cables. This level of infrastructure is infeasible for CH applications. Thus, scalability, complexity of deployment, and high cost are disadvantages of this approach.

Complementing the Active Bat system, the MIT Cricket Localization System provides localization and orientation with centimeter accuracy [Priyantha et al.'00]. It is an excellent indoor localization system and various improvements have been made from the beginning [Priyantha'05; Wang et al.'07]. Cricket implements both the lateration and proximity techniques and uses a combination of RF and US technologies to provide location information to attached host devices. RF signal is used to carry messages such as ID, temperature and designated coordinates, while US provides only a pulse. Cricket system is composed of two different devices, the beacon and the listener.

Beacons are fixed on the indoor ceilings with their own definite coordinates and with a predefined layout and a predefined distance. Listeners are attached to mobile devices and listen for RF signals sent by beacons mounted in wall and ceiling, and upon receipt of the first few bits, listen for the corresponding ultrasonic pulse. When this pulse arrives, the listener obtains a distance estimated for the corresponding beacon by taking advantage of the difference in propagation speeds between RF (speed of light) and US (speed of sound). The listener runs algorithms that correlate RF and US samples and to pick the best correlation. In addition to determining spaces and estimating position coordinates, Cricket provides an indoor orientation capability via the Cricket compass.

The Cricket system has different advantages, such as privacy and decentralized scalability, but its disadvantages include computational burden that timing and processing both the US pulses and RF data place on the mobile receivers. Furthermore, even if accurate, both systems suffer from a high installation and maintenance cost.

2.3.3.2 Infrared localization systems

Infrared (IR) localization systems are based on IR transceivers that are inexpensive, compact and low power. They are characterized by non-interference with other electronics devices, even if they suffer from interference from ambient light and from other IR devices in the environment. Their typical range is up to 5 meters.

Active Badge was the first IR based location system. It was developed at Olivetti Research Laboratory, now AT&T Cambridge [Want et al.'92] and consists of a cellular proximity system. Each person the system can locate wears a small IR badge that emits a globally unique identifier every 10 seconds or on demand. A central server collects this data from fixed IR sensors around the building, aggregates it, and provides an application programming interface for using the data. A badge's location is symbolic, representing, for example, the room in which the badge is located. IR systems have difficulty in locations with fluorescent lighting or direct sunlight because of the spurious IR emissions these light sources generate. Diffuse IR has an effective range of several meters. To obtain a higher resolution the system can use multiple IR beacons.

Several applications that exploit IR technologies have been developed also in the CH domain. The Hippie/HIPS project [Oppermann et al.'00] has developed an exhibition guide, which provides guidance and information services. The mobile device senses IR beacons installed near all exhibits, providing the users with the information related to the artwork nearest to them. The project also addresses the problem of how to adapt the user interface to the user model. HIPS processes all the observations about the visitor's journey through the exhibition and uses them to create a user profile and suggests interesting exhibits augmenting them with background information. The model can be modified by the user or by the system considering the user preferences detected during the visit, making proposals to the visitor. The system is however limited in detecting nearby artwork, because it detects only the position without the direction. This could imply an erroneous detection of the nearby exhibition, that wrongly could change the user model. The authors of IrReal [Butz et al.'04] implemented a building information and navigation system based on Palm Pilot PDAs and a set of IR transmitters located throughout a building. Information is grouped in a cluster of pages and when the user moves in the building the IR emitters send relevant data related with their position. The main idea is to use infrared senders to broadcast all information, so neither a large database nor a radio network card have to be installed on the mobile devices. This solution has some drawbacks related to the fact that each transmitter is able to send only predetermined data, related to the object nearby. The user does not have the possibility to see other contents. Furthermore, the solution is quite expensive and obtrusive, due to the fact that each beacon is connected with a PC to broadcast contents.

2.3.3.3 Radio localization systems

Radio-frequency (RF) signals offer several benefits over IR, because they do not have the strictly requirement of a "line of sight", passing through common building materials. Since the

RF spectrum is heavily regulated, typical systems operate at 900MHz or 2.45GHz and comply with Part 15 FCC regulations, making them not require license.

Localization methods exploited by RF systems are based on temporal information or signal attenuation. While the use of temporal information requires ad-hoc device, signal attenuation is limited by the RF signal non-linearity with distance and on the non-Gaussian noise, resulting from multipath effects and environmental effects, such as building geometry, network traffic, presence of people, and atmospheric conditions. In order to overcome these problems radio localization systems typically exploit fingerprinting methods to estimate the position. The most important radio localization systems, presented in this section, are WLAN, Bluetooth, Zigbee and UWB.

2.3.3.3.1 WLAN based positioning system

Wireless Local Area Networks (WLANs) usually refer to IEEE 802.11 networks (also called WiFi networks). It is an international standard describing the characteristics of wireless connection. This standard is divided in many substandards and currently the most widely used are 802.11a, 802.11b, 802.11g.

A WLAN network is composed of at least one Access Point (AP) and devices equipped with a WLAN card. Normally the AP transmits periodically (default rate 100 ms) beacon frames to signal its presence to mobile devices (infrastructure mode). Transmitted beacons are very important for localization, since they contain information such as a timestamp, supported data rates and the AP's cell identifier, the so-called Basic Service Set Identifier (BSSI). WiFi devices listen to all possible channels for receiving beacons from nearby transmitters and connect themselves to the AP with the best signal quality.

Today WLAN installations are available in many public (airports, universities, hospitals, train stations, tribunals, etc), commercial (restaurants, hotels, shopping center, etc) and private buildings. Also several sites are equipped with WiFi connections. Considering that PDA and smart phones are almost all equipped with WLAN connectivity, it is appealing to use an existing WLAN infrastructure for indoor location as well. This kind of localization system has different advantages. First of all, it is an economical solution, as it is based on existing infrastructure with communication capabilities. For mobile devices equipped with WLAN card, it can be implemented simply in software, significantly reducing cost with respect to dedicated architectures. Secondly, WLAN positioning systems cover large areas compared to other types of indoor positioning systems, working in a large building or even across many buildings. Thirdly, it is a robust system due to its robust RF signal propagation. Video- or IR-based location systems are subject to restrictions, such as line-of-sight limitations or poor performance with fluorescent lighting or in direct sunlight. Despite all these advantages it has some major

drawbacks that limit its usage. Many existent infrastructures have not got the best configuration for a good localization. The placement of APs for communication purpose aims to provide maximum coverage with minimal APs. While, as shown in [Xiang et al.'04], WLAN localization system accuracy is greatly affected by the number of APs. In general, to achieve an acceptable accuracy, it is better to add more APs in the area: for each position in the area covered by the WLAN signal, there should be at least three or four access points. Furthermore, problems like interferences, disturbances and multipath highly influences the accuracy of WLAN localization systems.

In recent years, several researches have been conducted concerning this technology. A selective overview of the most interesting is presented here.

Typically a WLAN localization system can exploit two different information: temporal information (like TOA), that requires a synchronization procedure, or Received Signal Strength information (RSSI) together with Signal to Noise Ratio (SNR).

Several commercial solutions tried to exploit temporal information. This kind of localization however require device modification, like for instance the solution proposed by Hitachi [Hitachi]. Some efforts has been done to understand the feasibility of this approach with standard components, like the study conducted by the University of Berlin, concerning the degree of accuracy to which the propagation delay of WLAN packets can be measured using today's commercial and inexpensive equipment [Günther et al.'05]. In general both temporal based technique and RSSI based techniques suffer from multi-path conditions, causing the degrade of the estimated position.

Using RSSI information to determine the user position two different methods can be applied. The former is called fingerprinting, the latter uses a propagation model that relates the detected signal strength with the distance from the AP. In order to obtain a better performance the two approach could also be used together.

The fingerprinting method was introduced for the first time by Microsoft Research in the RADAR project [Bahl et al.'00b], that adopted the nearest neighbors in signal space algorithm. The achieved accuracy is about 2-3 m. In the successive work they increase the accuracy by introducing a Viterbi-like algorithm [Bahl et al.'00a].

From this work several projects based on fingerprinting technique [Xiang et al.'04] and several commercial solutions have been developed. The WiFi Positioning System (WPS) from Skyhook Wireless [Skyhook] is a software-only location platform that provides 20 meter positioning accuracy to any WiFi enabled mobile device. Skyhook has developed a vehicle-based signal scanning and data collection technologies in order to capture the data output of individual APs and pair them with a date, time and location stamp at the point they are received by the data collection device. The data collection device captures signal readings every second so that over the course of time, the device will collect several signal readings of just one AP.

This survey method creates a “fingerprint” of the signal generated by that AP. When a device, application or service requests location, WPS initiates a scan to collect data on nearby AP, compare the collected data of MAC addresses and RSSIs for each AP in range against the data store of previously identified APs and then calculate the location of the requesting device.

Ekahau Inc. [Ekahau] is another commercial system that offers a wireless location-sensing system. It uses a radio map with reference points and claims to offer the “most precise real-time location tracking available on the market”.

A WLAN localization system developed by the department of computer science at the Humboldt Universität Berlin is Magicmap [Ibach et al.'05]. It uses an hybrid process that include the fingerprinting and a propagation model based method. Moreover MagicMap follows a collaborative approach in which clients share information on AP positions and reference measurements. An averaged k-nearest-neighbors principle is used with reference measurements stored during a calibration phase. In theory MagicMap should require very little initial information, like for example position of some APs, but it is not able to provide fine grain spatial information, reaching a resolution of six meters.

Even if radio signals do not need line of sight, the RSSI strongly depends on the line-of-sight with the AP, and can change depending on the orientation of the user, i.e. north, south, west and east, on the weather and on closer hardware. Furthermore, “environmental variations cause significant fluctuations in WiFi signals in the same location over time, rendering traditional RF-to-location pre-trained maps quickly obsolete” [Ho et al.'06]. In order to overcome this problem Ho et. al., proposed a method to re-train and dynamically update the system when the location estimation is wrong.

Recent works on WiFi based localization systems use probabilistic methods. In order to determine the user’s position, probabilistic techniques construct a probability distribution over the targets location for the physical area, making up the environment. Horus system, i.e. [Youssef et al.'02; Youssef et al.'05], lies in the probabilistic techniques category. It identifies the various causes of variations in a wireless channel and developed solutions to overcome them. In particular it models the signal strength distributions received from AP using parametric and non-parametric distributions. It uses location-clustering techniques to reduce the computational requirements of the algorithm. The experiment results show that this technique can has an accuracy within 2 m.

Nibble [Castro et al.'01], one of the first systems of this generation, uses Bayesian networks for inferring location in a WiFi network. In [Roos et al.'02] a grid-based Bayesian location-sensing system has been implemented.

Battiti [Battiti et al.'02] proposes a localization method based on neural networks and a training algorithm based on second order information for reducing the errors in the determination of the current location of the user. The average accuracy reached when the

environmental changes during the day is of approximately 2.3 meters. [Krumm et al.'03] introduced a number of techniques for simplifying the process of calibrating a location sensing system, by reducing the time spent at each location and reducing the number of locations visited.

The reported systems are representative of the effort in research to develop a location system based on WiFi technology. Even if the great effort, these systems are hampered by inherent technology problems such as limits on coverage, signal interference, and reliance on infrastructure, and by broader issues such as privacy concerns. To increase the WLAN positioning accuracy others sensors should be added. An interesting solution is provided in [Evannou'07], where the position is obtained using an algorithm based on Particle Filters and Voronoi diagrams, that limit the walkable area

2.3.3.3.2 Bluetooth

Bluetooth (IEEE 802.15) is a standard communications protocol for low cost, low power consumption, short range radio technology developed to connect devices such as mobile phones, PDA, portable computers and headsets. The integration of Bluetooth on a variety of devices and their low power consumption with respect to WiFi technologies pushed the research to find localization technique based on it. Bluetooth tags are small transceivers and each tag has a unique ID associated. The communication speed of Bluetooth devices is theoretically 1Mbps. The protocol consists of a first step called “discovery” in which the device have to discover if other devices are in range. Usually this step takes in terms of time between 5 and 10 seconds. The second step is the normal phase, that ends when one of the two devices is not anymore in range. The initial step could be a problem in systems that need to be reactive in proposing services. Another problem could be the maximum size allowable of the piconet.

Approaches used to locate users using Bluetooth similar to radio technology localization systems like WLAN. In [Rodriguez et al.'05], for example, a localization system similar to RADAR project, but using radio-frequency technology provided by a Bluetooth network, has been developed.

A system called the Bluetooth Local Positioning Application (BPLA) has been developed in [Kotanen et al.'03]. Positioning is based on received signal power levels that are converted to distance estimated according to a simple propagation model. An Extended Kalman Filter is used to compute 3-D position estimates on the basis of distance estimates. The accuracy of BLPA is reported to be 3.76 m.

Even if Bluetooth is a low cost, low power and ubiquitous location system, it cannot achieve high accuracy. Indeed in open spaces without obstruction or walls, it provides a precision of ~2 meter. In a compartmented space, such accuracy can decrease, requiring a

supplementary mechanism. A possibly integrated solution is Tadlys' indoor location system, named Topaz [Topaz], based on Bluetooth enhanced by IR. In order to detect which room the user is inside, the IR is a good solution, as light waves cannot penetrate opaque objects, thus remaining confined within the room's walls. This system provides 2-m spatial accuracy, with 95% reliability and a positioning delay of 15–30 s.

2.3.3.3 Zigbee

The ZigBee is “an emerging standard that is based on the IEEE 802.15.4 and adds network construction (star networks, peer to peer/mesh networks, and cluster tree networks), application services, and more”. Compared to other positioning technology like GPS, GSM, Bluetooth and IR, the Zigbee sensing infrastructure is cheaper, easier to deploy, and more accurate position technology. The range of the radio transceivers are typically 20-30 meters, and the defined data rates vary from 20 to a maximum of 230 kbit/s. Despite the low bandwidth nature of a Zigbee network, its capacity is sufficient for sending location information in real-time, low power consumption fashion. The growth of IEEE 802.15.4 wireless PANs (WPAN) in recent years suggests an interesting future for the location fingerprinting technique. Zigbee based location systems use RSSI to estimate user position. Till now few localization algorithms based on Zigbee have been developed.

Sugano in [Sugano et al.'06] implemented a positional estimation technique using RSSI in a sensor network in accordance with the ZigBee standard and evaluated its position-estimation ability. Ecolocation [Yedavalli et al.'05] is a localization algorithm that has been evaluated on a real sensor network that uses a low power wireless radio, reporting a location error of 10ft for a very small outdoor network deployment area (26ft x 49ft).

The main advantage over other localization system is that ZigBee transceivers are low powered, small and inexpensive. ZigBee positioning units reportedly have a battery life span with regular AAA batteries that may exceed several years, in applications when an update rate of several minutes is sufficient. Typically a battery-powered node can wake up, check in, send data, and shut down in less than 30 ms. Furthermore, it does not need an infrastructure, because stationary nodes placed in the rooms autonomously can estimate their own positions. On the other hand penetration through walls is very limited; thus, several nodes must be placed in every room.

In museum environments this system could imply to set transceivers in the different rooms, that could require the installation of an unfeasible amount of sensors must be placed in order to achieve sufficient accuracy. An unobtrusive solution that includes the use of this technology, consists in using ZigBee as “gapfillers” during the development of more capable, infrastructure-less positioning systems.

2.3.3.3.4 RFID

Radio Frequency Identification (RFID) is a technology developed since the 1960s. It is primarily used today for applications like asset management, access control, textile identification, collecting tolls, or factory automation.

RFID systems are composed of two key elements - transponder (tags that are attached to the object) and reader. Communication between the RFID readers and tags occurs wirelessly and does not require a line of sight between the devices. In general readers search for a tag that is within range by sending out a predefined RF signal. A tag that receives this signal responds back with its unique ID that has been preprogrammed in its memory. Two different kinds of RFID tags are available: active and passive tags. An active tag is equipped with power supply in the form of a battery, while the latter extracts the required energy from the radio signals emitted by the readers. This aspect has fundamental impact on the communication range: active tags typically bridge distances of several tens of meters, while passive tags have a range between tens of centimeters and a few meters. Furthermore, passive tags have small memories where they store their ID. Frequency of RFID system can be classified as high-frequency (850–950 MHz and 2.4–5 GHz), intermediate-frequency (10–15 MHz), and low frequency (100–500 kHz) systems. The communication range and cost of RFID systems depend on the frequency range.

Two different approaches can be used to develop RFID systems. In a network based approach the readers, installed in the building, are connected to a central server. People to be located carry a tag that univocally identifies the mobile user. In a terminal-based approach the reader is connected to the mobile device and tags are installed in the building. The reader catches location data from the tags when they are close by.

Multiple localization methods using RFID technology have been implemented. SpotON [Hightower et al.'00] is a location sensing system which utilizes radio signal attenuation to estimate the distance of mobile devices equipped with active tags to the base stations. A central server then aggregates the values to estimate the position of the tagged object. Finally, the computed object positions are published to client applications.

Another well known application is LANDMARC [Ni et al.'04], that exploits similar principles to SpotON. It employs extra fixed location reference tags to help location calibration. These reference tags serve as reference points in the system. It measures the tracking tag's nearness to reference tags by the comparison of their signal received in multiple readers. The algorithm implemented in LANDMARC uses the weighted sum (the weight is proportional to the nearness) of the positions of reference tags to determine the 2D position of the tag being tracked. The main drawback is related to the fact that both LANDMARC and SpotON utilize active tags that have limited lifetime.

In the Guide project [Philipose et al.'03] static RFID readers are employed to detect human interaction with passive RFID tagged objects. In particular the proposed technique detects when the user moves or rotates, waves a hand in front of objects, and walks in front of objects. The project however does not take in account the estimation of positions of RFID tagged objects. Their experimental results show that their system could nearly always detect rotations, while the system performed poorly in detecting translation-only movement. The Ferret system [Liu et al.'06] on the other hand is able to also locate nomadic objects augmented with passive RFID tags, displaying user position in real-time. Authors present two different algorithms: an offline algorithm to map the detection probability and form a dataset of the location of the tag and an online algorithm for real-time use on a mobile device reducing complexity over the offline technique. Ferret focuses also on the problem posed by the integration of a handheld device and nomadic objects. The evaluation shows that Ferret can detect nomadic objects with 100% accuracy when the nomadic distances exceed 20cm.

RFID localization has also been used to develop CH multimedia guides, like I-Guide [Hsi'04] a research project that took place at the Exploratorium, a museum of science, art, and human perception. This project uses RFID to provide localization of Points-Of-Interest and content. In addition, it allows people to bookmark interesting exhibits they would like to remember. Another interesting project is Cicero, a system based on a PDA augmented with an accelerometer, infrared technology and a short-range RFID reader and the interaction exploits tilt-based gestures and RFID-based physical selection for accessing artwork information to enable a more natural visitor interaction. The infrared signal detects when the visitor enters a space, and simultaneously a map of the room is provided automatically. The visitor then scans a RFID tag associated with an object by physical selection, and the object is highlighted graphically on the room map. That is, information on a mobile device is associated to an object in the physical environment. In the detailed data-view, navigation among different pieces of information can be done by tilting horizontally [Mäntyjärvi et al.'06].

In conclusion, RFID tags are cheap and small, in particular the passive ones. They could be hidden in the environment without resulting obtrusive and above all they do not need an external infrastructure.

2.3.3.3.5 Ultra-Wide Band (UWB)

Ultra-Wide Band (UWB) is a recent radio technology. It occupies a wide bandwidth (typically 1000MHz) and can be used at very low energy levels for short-range communications (up to 10 meters). UWB has applications in target sensor data collection, precision locating and tracking applications. In particular, thanks to the extremely large bandwidth UWB signals offer a good multipath resolution and enable accurate positioning [Miller'03].

UWB positioning approaches can be divided into ToA, AoA and RSS based systems [Patwari et al.'05]. Advantages of UWB positioning include less power consumption than conventional RF tags, penetration of walls and other solid objects, resistance to multipath (or Raleigh) fading, in fact UWB short duration pulses are easy to filter in order to minimize the multipath distortions that are the main cause of inaccuracy in RF indoor location systems. However metallic and liquid materials cause UWB signal problems.

Even if it can be considered a new technology, several studies have been conducted to understand the localization perspective.

In [Lee et al.'02] the authors propose a ToA based ranging technique using an UWB radio link. The ranging scheme utilizes generalized maximum likelihood and implements a search algorithm for the detection of direct path.

[Gigl et al.'07] designs an indoor UWB ranging and positioning system using the RSSI. This approach enables trilateration based position estimation while significantly reducing the synchronization effort. Ranging based on the RSS is very sensitive to the estimated pathloss model parameters. For this reason a number of calibration measurements in the positioning area are required. A better placement of the base stations could bring better accuracies through better geometrical conditioning. The achievable accuracy decreases with the distance, so close BSs have to be available in UWB positioning based on RSS.

Also commercial systems have been developed. Ubisense [Ubisense] for instance provides an automatic localization system by using UWB technology platforms. It works by creating sensor cells. Each cell requires at least four sensors or readers. Throughout buildings or collections of buildings, an unlimited number of readers can be networked together in a manner similar to cellular phone networks. Ubisense delivers 15cm 3D accuracy in real-time with the ability to monitor thousands of people and assets.

UWB provides dramatic channel capacity at short range that limits interference, thanks to its frequency range operation. UWB short-range technology, complements other longer radio technologies such as GSM, UMTS, WiFi.

2.3.4 Navigation by Vision

Pedestrian detection from images is an active area of research, used also to design pedestrian protection systems. Research in pedestrian navigation by vision is important for both government organizations and commercial activity.

An interesting review of the state-of-the-art tracking methods is proposed in [Yilmaz et al.'06]. In [Darrell et al.'00] it is shown as multimodal processing (silhouette, skin color, and face pattern) can significantly enhance accuracy. Improved systems, in order to achieve higher

grades of robustness, rely on Stereo-Vision systems [Segvic et al.'03; Salmon et al.'06]; we explore this aspect in section 3.2.

Two different approaches can be used to detect user's position. First, the building can be equipped with cameras, which look for the moving objects. A second approach consists in equipping mobile user with a small camera. Visual tags are attached on walls inside the building. In this case, the visual tags have fixed positions. If the mobile camera detects two or more tags, it can find out its own position.

An interesting museum guidance system based on navigation by vision is presented in [Bruns et al.'07]. Bruns et al. developed a system called PhoneGuide that uses widespread camera-equipped mobile phones for on-device object recognition in combination with pervasive tracking. They carry out all computations directly on mobile phones, ensuring little or no network traffic during runtime and consequently eliminates the cost for online time. Such an approach enables object recognition from a distance without additional aids. Considering that vision-based object recognition methods do not scale well, they proposed a combination of pervasive tracking (using only a coarse grid of emitters) and on-device object recognition, a scalable system with a high recognition rate can be realized.

There are several advantages in using vision system, especially concerning museums. In fact vision systems can simultaneously support repositioning of multimedia guides equipped with inertial sensors and multiple museum services, such as visitor flow monitoring and statistical information gathering about the visitors' behaviour, and therefore maximize the cost-effectiveness of the required installation.

2.3.5 Dead Reckoning Systems

In situations where GPS/Galileo signal or cellular navigation are not reliable or do not work at all, an alternative positioning systems able to detect user's location is required.

A solution that does not require to change environment to fit the needs of the tracking system and does not rely on ad hoc infrastructure, i.e. Ultra-Wideband (UWB), WLAN, Bluetooth (BT), is based on a MEMS-based Inertial Measurement Units (IMU). It uses typically a triad of accelerometer and gyroscope, that provide continuously measurement outputs, independent of the environment. It is used in a wide range of fields including both more critical applications, such as aircraft and cruise missiles, spacecrafts, submarines and ships, and less critical ones, such as leisure applications, video games, and in the CH domain.

Two different methods are used for tracking people with IMU. The first processes the IMU measurements through a set of mechanization equations to compute a navigation solution. Such an algorithm is referred to as an Inertial Navigation System (INS) algorithm, in which the

position is estimated by a double integration of accelerations. This approach however suffers from error accumulation, because even a small error in acceleration builds upon time [Judd'97].

The second algorithm totally avoids integration of measurements, but makes use of walk dynamics contained in the accelerometer signals such as frequency, maximum/minimum amplitude. This algorithm is termed as pedestrian dead-reckoning (PDR) algorithm.

The positioning task is often performed by rigidly connecting the IMU to the human body, i.e. on the belt, in such a way it can sense user movement. Several types of sensors can be used. For instance, using the accelerometer signal pattern, it is possible to deduce the step occurrences and using gyroscopes it is possible to estimate heading information.

Considering that the integration phase used by the INS algorithm introduces the error, in this thesis only the PDR algorithm is considered.

PDR platforms yield accuracy of less than a meter, adequate for a lot of precise indoor/outdoor applications. Precise PDR systems were inaccessible a decade ago, due to the lack of technology. The development of micro-electromechanical systems (MEMS) has allowed the design of cheap, small and lightweight sensors based on the same principles of the location systems found in boats or airplanes.

Due to the nature of this research, we are interested in developing an accurate PDR system requiring only one sensing device mounted the user's body, with low costs sensors and low power consumption.

2.3.5.1 Dead reckoning sensors

Dead reckoning platforms are usually realized using MEMS sensors, i.e. accelerometers and gyroscopes [MEMS], and non inertial sensors, i.e. magnetometers and barometers. They are mounted on a device worn by the user. In this way the device experiences the same movements of the human body.

MEMS sensors expose different advantages [Titterton et al.'04] like:

- small size;
- low weight;
- low power consumption;
- short start-up time;
- inexpensive to produce (in high volume);
- high reliability;
- low maintenance;
- compatible with operations in hostile environments;

Originally MEMS sensors were not specifically developed for positioning, indeed the big market of MEMS accelerometers and gyros comes from the automotive industry, e.g. in crash-

detectors, with primary goals of cost reduction and reliability – not size. Even so, their use in pedestrian navigation is now widespread, with great advantages for both indoor and outdoor navigation.

2.3.5.1.1 MEMS Gyroscope

MEMS-gyroscope consists of a vibrating structure, such as a ring, fork, plate or mass-pair. A MEMS-gyro senses rotation by means of Coriolis-force interaction between a driven (excited) vibration mode and a quadrature response (detection) mode. It gives an output proportional to the angle through which it has been rotated. The natural frequency is typically a few kHz up to 15 kHz [Rantakokko et al.'07]. A summary of MEMS-gyro error sources are listed in [Woodman'07]. The majority of observed errors are:

- **Temperature drift:** gyroscopes are susceptible to *sensor thermal drift* error. *Thermal drift* is a characteristic error source that is inherent to the sensor design and unique to every sensor. It causes a constant, measured angular rate value to drift with respect to ambient temperature. If the gyroscopes are not suitably calibrated and compensated for thermal drift, the sensors can introduce severe measurement errors while operating under changing ambient temperature conditions.
- **Scale-factor and offsets:** the X, Y and Z axis gyroscope produce different outputs when subjected to a given angular rate. Thus, this value has to be determined and referred to a sensor scale factor. The offset of a gyro is given by the gyro output under stationary conditions (0 angular rate input). This parameter is not a constant and unique to every gyroscope. The error induced due to gyro offset has to be compensated.
- **Scale-factor non-linearity:** the scale factor of MEMS gyroscopes is non-linear over the measurement span.
- **Scale-factor dependency on temperature:** the gyro scale factor exhibits a dependency on operating ambient temperature. Thus any scale factor dependency on operating ambient temperature has to be captured during gyro scale factor calibration.

MEMS-gyroscopes are able to detect angular velocity with high precision, but it can only be used for a short time to calculate angular orientation. Hence a relatively small offset error due to temperature effects on the gyroscope signal will introduce large integration errors.

A well performed calibration is required to reduce error related to bias and scale factor errors. Sudden rotations measured by the gyroscope can result in a saturation that leads to a wrong measurement. Furthermore, the integration of the rotational velocity results in a significant error which is due to an offset drift caused by the temperature variations. This is why the gyroscope needs to be calibrated based on temperature in order to reduce these type of errors.

2.3.5.1.2 MEMS Accelerometer

The MEMS-accelerometer is perhaps the simplest *MEMS* device, sometimes consisting of a hinged proof mass (also known as seismic mass), thus resembling a pendulous accelerometer, with some type of deflection sensing and circuitry. MEMS accelerometers are available in single-axis, dual-axis, and three-axis models. They are sensitive to both gravity induced static acceleration and movement induced dynamic acceleration. Accelerometers measure the vector sum of acceleration and gravitational acceleration in sensor coordinates. In [Luinge et al.'04] is shown how the gravitational component, having a bigger magnitude for many human movements and pointing always downward, can be used to estimate the angle between the horizontal and the vertical planes. This measurement, also called tilt, does not suffer from integration drift and in theory could be used to correct the drifted orientation estimate from the gyroscopes.

The major error sources of MEMS accelerometer are:

- **Offset and scale factor:** in general, MEMS-accelerometers are not calibrated post-production, resulting in a scale factor S and offset on each of their measurement axes. Hence, accelerometers need to be calibrated individually in order to determine their offset and scale factor.
- **Temperature drift:** this is an error source inherent to the sensor design and unique to every sensor. It causes a constant, measured acceleration value to drift with respect to ambient temperature. If the accelerometer is not suitably calibrated and compensated for thermal drift, it can introduce severe measurement errors while operating under changing ambient temperature conditions.
- **Cross-axis error:** this error is present when more than one accelerometer is mounted on a board. The axis of the sensors are often misaligned from perfect orthogonality. This misalignment introduces erroneous sensor measurements.
- **Non linearity response:** Due to the nonlinearity the accelerometer is most sensitive when the sensing axis is closer to 0° , and less sensitive when closer to 90° . To solve this problem the degree resolution of the application must be determined at 0° and 90° to ensure the lowest resolution is still within the required application resolution.

2.3.5.1.3 Magnetic Compass

Electronic compasses based on magnetic sensors are able to detect the earth's magnetic field, providing heading information to PDR systems. The main problem related with this type of sensor is that the measured earth field may be superimposed by other magnetic fields or distorted by nearby ferrous materials. An efficient compensation of such effects is required in

order to achieve reliable azimuth readings [Stork]. The compensation is able to reduce error caused by deterministic interference sources. Deterministic means that the interference source is at a fixed position relative to the compass and that its magnitude is constant versus time. Basically, two kinds of determinist interference can occur, called “hard iron effects” and “soft iron effects”. “Hard iron effects” are caused by magnetized objects, which are at a fixed position with respect to the compass. “Soft iron effects” occur due to distortion of the earth field by ferromagnetic materials. In practice, hard iron effects dominate over soft iron effects and can be minimized first of all by not installing the compass near objects producing strong magnetic fields. Typically in PDR systems two or three axis compass are integrated to detect the azimuth.

2.3.5.2 Pedestrian Dead Reckoning Techniques

PDR estimates a user’s current position based on a previously determined position, and advancing that position based upon known step length (or walking speed) and direction of walking. These entities must therefore be estimated, or modeled through different sensors. The displacements are generally expressed in terms of changes in Cartesian coordinates, i.e. x and y coordinates. The basic principle for a dead-reckoning system is illustrated in Figure 3.

Several human walking analysis have been conducted [Cavagna et al.'66], showing the way a body moves during a gait cycle and the logical relationship between step size and walking speed. An extensive research on body activity detection is reported in [Sutherland'02].

Typically PDR systems are complex to develop, due to the fact that they have to cope with general motions and detect different movements, including walking, jogging, running and sprinting. The PDR algorithm avoids integration of measurements, but rather make use of walk dynamics contained in the accelerometer signals, i.e. frequency, maximum/minimum amplitude. The algorithm detects the user’s trajectory mainly by decomposing the motion in three processes: step detection, step length estimation and heading estimation.

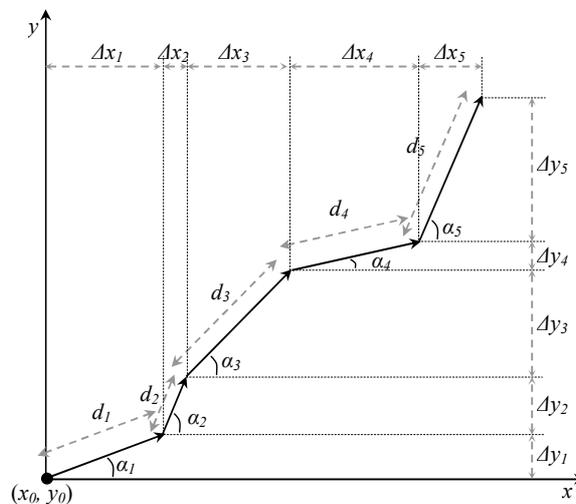


Figure 3. Dead reckoning navigation

Several methods have been proposed to detect step occurrences. In [Levi et al.'99] and [Jirawimut et al.'03] step occurrences are estimated by observing the peaks of vertical acceleration, i.e. acceleration perpendicular to the earth's ground plane. In [Cho et al.'02] the acceleration pattern is observed and when the rate of change of the accelerometer output is nearly zero, the condition of walking detection is satisfied.

Different approaches can be used also in step length estimation. For example in [Levi et al.'99; Ladetto'00] the step length is estimated via the stride model expressed by linear combination. The authors in [Aminian et al.] uses a walking speed model based on neural networks, while in [Cho et al.'02] and [Fyfe'99] a double integration of accelerations is performed. More details about step length estimation models and error analysis of the step length estimate, is reported in [Leppakoski et al.'02].

The heading detection involves the use of multiple sensors. The gravitational acceleration component provides inclination information and it is used to correct the drifted orientation estimated from the gyroscope and from the compass. Furthermore, the compensated yaw is integrated with the compass azimuth in order to have a more stable orientation, that does not suffer from magnetic disturbances. In [Harada et al.'03] a solution involving 2-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometers to measure the orientations of the device is proposed. Firstly, the absolute orientation is measured using the accelerometers and magnetometers. Secondly, the Unscented Kalman Filter integrates the measured absolute orientation with the local angular velocity, improving the stability and the robustness of the absolute orientation estimation.

Another approach that uses Kalman Filtering to estimate the user orientation is proposed in [Roetenberg et al.'05]. This approach combines the signals of a complete 3D sensor module including 3-axis gyroscope, 3-axis accelerometer 3-axis magnetometer. The Kalman filter weights the three sources of information appropriately with knowledge about the signal characteristics based on their models. The main difference from other approaches is that they have taken into account the static, quasi-static, and dynamic conditions, showing that the orientation estimates significantly improve using the magnetic interference correction and the filter overcomes both sensor and electronics drift.

2.3.5.3 Pedestrian Dead Reckoning Platforms

DR platforms with the appropriate algorithm provide reliable and accurate tracking information. Since these platforms provide only relative position, they are often combined with other absolute positioning sensors to provide starting points and reduce inertial errors, explained in Chapter 3. Several DR platforms have been developed both for commercial and research

purposes. Some interesting examples, that could be used in pedestrian navigation, are reported below. Table 1 resumes the most important characteristics together with the relative price.

The *InertiaCube* created by InterSense [Intersense] is an inertial 3-DOF orientation tracking system based on MEMS-gyroscopes, MEMS-accelerometers and magnetometers. The InertiaCube simultaneously measures 9 physical properties, namely angular rates, linear accelerations, and magnetic field components along all 3 axes. It is ideal for head or body tracking in mobile simulation, training and situational awareness applications.

Xsens Motion Tech [XSens] has developed different platforms that detect human motion, like *MTx*, *MTi* and *MTi-G*. They are used in a wide range of applications. MTx (in particular MT) unit has been used to demonstrate the possibilities of real-time motion analysis of speed skaters. It has also been used to develop a pedestrian navigation system using shoe-mounted sensors. The proposed technique is very accurate in terms of distance traveled and can handle many arbitrary manoeuvres, such as tight turns, side/back stepping and stair climbing [Beauregard'07]. The MTi-G is an integrated GPS and Inertial Measurement Unit (IMU) with an Attitude and Heading Reference System (AHRS) processor. The internal low-power signal processor runs a real-time Xsens Kalman Filter providing inertial enhanced horizontal and vertical position and velocity estimates (loosely coupled). It also provides drift-free GPS enhanced 3D orientation estimates, as well as calibrated 3D acceleration, 3D rate of turn (rate gyro) and 3D earth-magnetic field data.

The DRC Dead Reckoning Compass is built on Vectronix' proven Digital Magnetic Compass (DMC) technology [Vectronix]. It is a two dimension navigation system that integrates a microprocessor, three accelerometers and three magnetometers, and delivers a continuous DR relative position based on step detection and tilt compensated azimuth. The DRC provides an instantaneous absolute position based on any reference point input.

3D Motion Sensor is a platform developed by NEC TOKIN [Nec-Tokin] combining an accelerometer and magnetic sensor with a NEC Tokin Ceramic Gyro. It has been used to develop a wearable augmented reality systems [Tenmoku et al.'04]. This system obtains in real-time the position and orientation of the user exploiting positioning infrastructures in environments and the 3D Motion Sensor and the user's viewpoint orientation through the InterTrax2 of InterSense mounted on the user's headset. The system specifies the user's position using the position ID received from RFID tags or IrDA markers which are the components of positioning infrastructures. When the user goes away from them, the user's position is alternatively estimated by using a pedometer. IMUs product by Crossbow, Honeywell, Microbotics will not be taken in account because they are used for very accurate applications, implying an higher cost (> € 3,000), not sustainable in CH applications.

Sensor	Company	Sensors	Dimension	Price 1 piece
INU	Atair aerospace [Atair aerospace]	3D-Accelerometer 3D-gyroscope 3D-compass GPS	4.85x5.44x 3.10 cm 82 grams	n.a.
Crista IMU	Cloudcaptech [Cloudcaptech]	3D-Accelerometer 3D-gyroscope	5.21x 3.94x 2,5 cm 36.8 grams	< € 1,400
Terrella 6	Clymer Tech [ClymerTech]	3D-Accelerometer 3D-gyroscope 3D-compass	9.7x1.6x1.3 cm	€ 1,500
InertiaCube3	InterSense [Intersense]	3D-Accelerometer 3D-gyroscope 3D-compass	2.62x 3.92x 1.48 mm 17 grams	€ 1,420
InertiaCube3 Wireless	InterSense [Intersense]	3D-Accelerometer 3D-gyroscope 3D-compass	3.13x4.32 x14,8 mm 20 grams	€ 2,370
3DM-GX2	Microstrain [Microstrain]	3D-Accelerometer 3D-gyroscope 3D-magnetometer	4.1 x 6.3 x 3.2 cm 49 in enclosure	n.a.
3D Motion Sensor	Nec Tokin [Nec-Tokin]	3D-Accelerometer 3D-gyroscope 3D-compass	2.0×2.0×1.5 cm 5 grams	€800
MAG3	OmniInstruments [OmniInstruments]	3D-Accelerometer 3D-gyroscope 3D-compass	1.8x1.8x1mm 5 grams.	€ 1,200
Falcon GX	O-Navi [O-Navi]	3 gyroscopes 3 accelerometers	5.97x3.17x 1.52 cm 11,5 grams	From 500 to 700
MTx	XSensMotionTech [XSens]	3D-Accelerometer 3D-gyroscope 3D-compass	3.8x5.3x3.1 cm 30 grams	€ 1,750
MTi-G	XSensMotionTech [XSens]	3D-Accelerometer 3D-gyroscope 3D-compass GPS	5.8x5.8x3.3 cm 68 grams	€ 3,550
Dead Reckoning Compass (DRC)	Vectronix [Vectronix]	3 accelerometers 3 magnetometers	4.9 x 3.3 x 1.35 cm < 35 grams	n.a.

Table 1: IMU suitable for pedestrian navigation

Several universities and research centers have developed their IMU. For instance Intel developed *Mobile Sensor Board (MSU)* able to capture richer data to be used to infer a broader range of physical activities. The Intel-MSU contains seven types of sensors, including an accelerometer; digital compass; barometric pressure, temperature, humidity and audio sensors; and three types of light sensors. The Intel-MSU is attached to the Intel® Mote, which contains Bluetooth wireless technology, enabling the board to communicate wirelessly with Bluetooth-enabled cell phones or other devices. The Intel-MSU is roughly the size of a pager and can be worn in a variety of locations [Lester et al.'05].

Another IMU, called Multi Sensor Unit (MSU) has been developed in our research center. It is an economical inertial solution that contains a 1-axis gyroscope, a 2-axis accelerometer and a 2-axis compass. A detailed description of the MSU will be provided in chapter 3.

2.5 Location information and space models

When dealing with location system it is important to understand what the location information is referred. Two different types of localization data can be provided, that is physical and symbolic location [Hightower et al.'01].

Physical location is related to the position of a user within a reference system that models the entire Earth. The reference system is composed by the coordinate system (i.e. Cartesian Coordinate System, Ellipsoidal Coordinate System, etc.), the datum (i.e. horizontal datum, vertical datum), and the map projection (i.e. Mercator projection, Universal Transverse Mercator) [Kupper'05].

The symbolic location is related to an arbitrary location, like for instance a point of interest (POI). It is sometimes argued that location is best identified by global coordinates or absolute reference systems. However, if the CH domain is considered, symbolic references tend to be more precise. The standard routing in pedestrian navigation systems is the guidance from “point of interest” to “point of interest” along a predetermined or a chosen tour.

Both for context aware content access and orienteering purposes, the application has to know the space model. This knowledge, is usually supplied by a GIS system. “GIS can be viewed as an integrated technology, which merges the precise location and associated attributed of natural and man-made feature. The combination of conveys the “what” and “where” of a feature or object on the Earth’s surface and is the foundation upon which a wide range of information can be integrated and displayed” [DIGO'02].

2.6 Abstracting location

The big challenge in location-aware systems is the creation of a location-aware application that works both outdoors and indoors. Research in localization system aims to conceive a technology that is available with the same level of accuracy and resolution in every type of environment. A location system could be availability all the time, if a decreased accuracy is accepted. Accuracy and availability are two trade-offs and most of the times less accuracy induces an increase of the availability.

During the last years several location systems have been proposed that use multiple technologies simultaneously in order to increase the accuracy. This approach is known as sensor data fusion which aims to improve accuracy and availability by integrating heterogeneous sensor observations.

2.6.1 Multi Sensor Approach

When using a single type of sensor it is not possible to assure a continuous tracking of the user. For being effective pedestrian tracking system usually integrate and combine several different sensor in order to:

- Deal with uncertainty caused by one single sensor;
- Integrate different measurements to come up with a precise determination;
- Deal with different environment condition that can preclude the use of a particular sensor, i.e. GPS indoor or in urban canyon.

Therefore appropriate location sensors have to be combined and integrated using a new multi-sensor fusion model. The model must be able to make full use of all available single observations of the sensors at a certain time to obtain an optimal estimate of the current user state, i.e. position, orientation and motion. The goal however should not be to use all the sensors all the time, but select appropriate sensor data and integrate it when and where needed. It is important to underline that in order to avoid situation of power waste, a good method is to switch off sensor where they can not provide accurate measurements.

Developing a location system that uses more than one sensor it is possible to identify three different parts: sensors to sense a certain physical attribute, an algorithm that compute position from the measurements gathered from the sensors and an algorithm that combines information coming from different sensors and estimate the final user position.

Location researchers have used different algorithms and methods to incorporate sensor uncertainty like for instance Kalman filters [Kalman'60; Grewal et al.'93] or particle filters [Fox et al.'00; Doucet et al.'01]. In the field of pedestrian positioning a lot of work has been done to obtain a reliable location system by integrating more than one sensor.

Two examples are reported below. Location Stack is a framework infrastructure for multi-sensor location-aware ubiquitous computing, while PlaceLab is a radio beacon-based approach to location providing low cost, easy-touse device positioning for location-enhanced computing applications.

2.6.1.1 Location Stack

Location Stack [Graumann et al.'03] is a six-layer framework for multi-sensor location-aware ubiquitous computing. The proposed framework is split in to six layers: the sensors layer, the measurements layer, the fusion layer, the arrangements layer, the contextual fusion layer and the activity layer. Each layer performs a specific task. Sensor layer is the lowest layer that detects changing state of the physical world. The measurements layer transcribes raw data into a more canonical form in order to be used by higher level layers. The fusion layer has received particular attention from the Location Stack project. It merges data using a probabilistic approach, in particular the Bayesian filter techniques including particle filters and multi-hypothesis tracking. The arrangements layer provides operators to relate the current probabilistic location estimates of multiple objects which are individually locatable using the Fusion layer interface.

The framework consists of a set of reliable distributed services communicating using asynchronous XML messages and remote procedure calls. Services are connected using dynamic service discovery capability provided by the middleware.

The drawback of these systems is their inability of supporting mobile devices with limited capabilities (CPU, memory) as the location estimation is performed at the client side, hence devices incur the cost of complex computations.

2.6.1.2 PlaceLab

The Place Lab [Lamarca et al.] is an unobtrusive radio beacon-based approach to location, that consists of three key elements: radio beacons in the environment (GSM, Bluetooth and WiFi), databases that hold information about beacons' locations, and the Place Lab clients that use this data to estimate their current location. The coverage and accuracy of Place Lab is dependent on the number and type of beacons in range of the client device.

The location estimation is performed on client side. The Place Lab client uses radio signal observations and cached beacon locations to estimate its location. Client functionalities are broken into three logical pieces: spotters, mappers and trackers. The spotter monitors the radio beacons and provides these information to the mapper that associate to known radio beacon the location. The tracker uses the stream of spotter observations and associated mapper data to produce estimates of the user's position. Tracker component performs the radio data fusion by using only the data provided to them by the spotter and mapper, or by using extra data like road paths and building locations to produce more accurate estimates. Place Lab includes a Bayesian particle filter tracker that can utilize beacon-specific range and propagation information. Experimental results conducted in Seattle show that using 802.11 and GSM beacons the system

is able to achieve 20-30 meter median accuracy with nearly 100% coverage measured by availability in people's daily lives.

This system, using different technologies allow a continuous tracking of the user. The achieved accuracy is not sufficient for precise indoor CH application, such as visitor guides, where a resolution of 2-3 meter is required.

2.6.2 Chosen Technologies for Integration

The following positioning technologies have been chosen to be integrated: Pedestrian Dead Reckoning systems, GPS, Vision Based Tracking systems and WiFi.

Pedestrian Dead Reckoning systems are unobtrusive localization system, because all the computation is performed onboard and external infrastructures are not required. Despite this, it requires initial information, as starting position and direction. For this reason Pedestrian Dead Reckoning systems needs to be combined with absolute localization systems.

GPS, as discussed, offers excellent solution for outdoor positioning identifications. Accurate positioning is nearly possible anywhere on Earth, 24 hours a day. The fact that GPS does not work well in urban and indoor locations, is overcome through the integration with the Pedestrian Dead Reckoning systems.

The Vision Based Tracking systems, even if more intrusive with respect to the previous ones, provide advantages that are not only related to the tracking of the user, like relevant museums services, i.e. like video-surveillance, people counting. Furthermore, tracking can be performed using only a single camera, not intrusive at all, that can be places in strategic positions, i.e. entrance door.

Wifi localization systems, ideally should work with already installed communication infrastructures, without requiring further installations. As radio frequency is not an optical technology, therefore it does not require Line of Sight (LoS). Furthermore it is able to uniquely identify object and people can be possible even on outdoor environment.

The smart integration of these technologies is the argument of Chapter 3.

2.7 Conclusions

This chapter illustrates localization methods and technologies used in pedestrian localization systems. Depending on the chosen location sensing technology and method, the accuracy can drastically change, as shown in Figure 4.

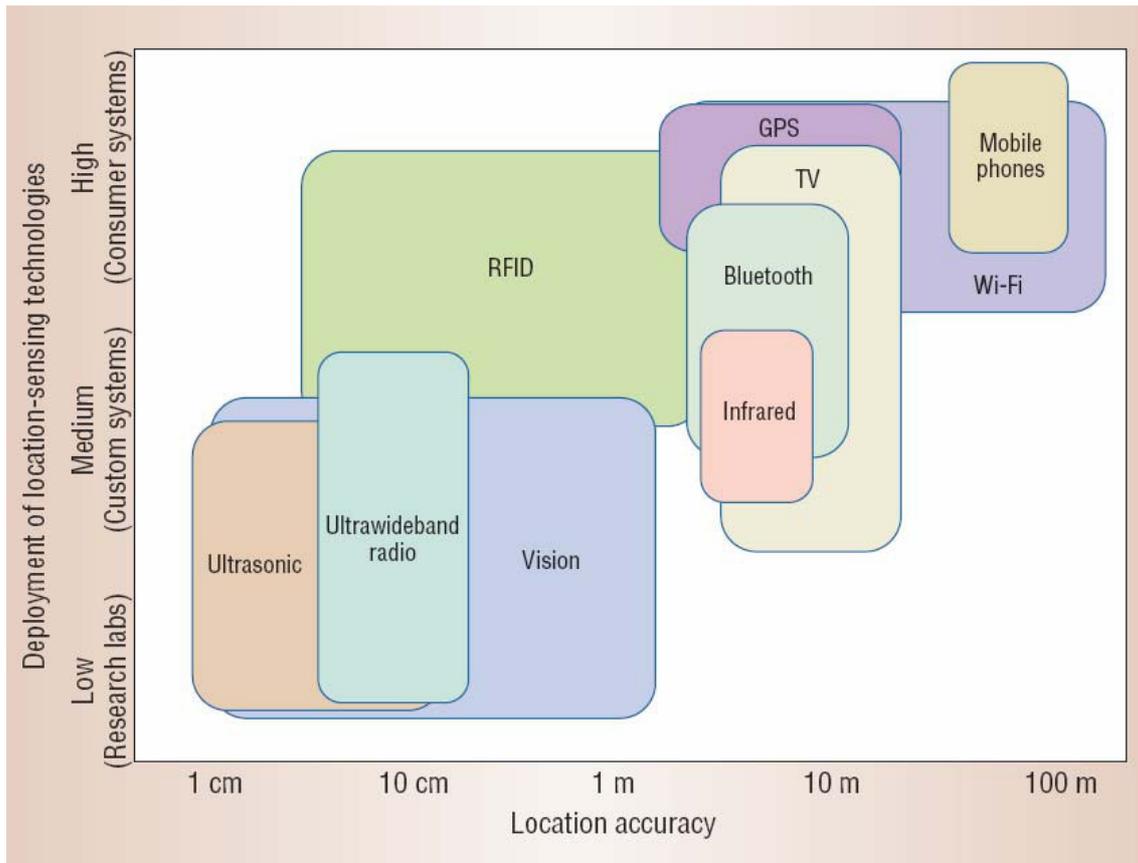


Figure 4: Location sensing technologies [Hazas et al.'04]

The brief overview of localization system highlighted how localization technologies are evolving. It is evident that we are still far from achieving the objective of having a self contained system, not dependant on external infrastructures. If this is not achievable, almost technologies used to locate users in ubicomp environments have to be discreet, without visible infrastructure and therefore able to locate users in every types of environment, maintaining always the same level of accuracy and precision.

Navigating in mixed indoor and outdoor areas is a very challenging task as pedestrians move in spaces where a single technology cannot work continuously in a proper way. Many systems are hampered by inherent limitation of technology, such as problems on coverage, signal interference, and issues related to the privacy. These limitation can only be overcome if different location technologies are combined in the sense of a modern multi-sensor system. The big effort in this direction is proved by the broad researcher done in universities and companies.

CHAPTER 3.

LOCALIZATION IN SMART ENVIRONMENTS

The main goal of this research is to provide a localization system aiming to reach the best compromise between intrusiveness, accuracy and cost. Ideally localization system should locate users both indoors and outdoors, with high resolution and no intrusiveness in the environment. It is nevertheless important to note that any positioning technology application is still not able to provide wide coverage and high accuracy simultaneously. Several localization technologies have been described in the previous chapter, and no one of them, used alone, is able to fulfill these requirements.

This chapter proposes a smart integration of different positioning technologies to increase the precision of the overall system. The proposed solution is a pedestrian navigation system, that combines a wearable inertial sensing platform (section 3.1) with absolute localization systems. The stereo vision tracking system, developed by Computer Vision Lab in University of Bologna (section 3.2) is used indoors to initialize position and direction and correct errors accumulated by the dead reckoning platform, while in outdoor environments, the GPS is exploited (section 3.3).

This chapter also discusses an alternative solution developed to localize users in indoor environments. This approach exploits the combination of Magicmap, a WiFi localization system together with 3D video tracking system [Ferrer-Biosca et al.'07], to provide pedestrian identification and tracking (section 3.4).

The first part of this chapter describes the architecture of the wearable inertial sensing platform, the algorithms used to track the users and their evaluation and results.

3.1 Multi-Sensor Unit: the Dead Reckoning Platform

In this work, a Multi-Sensor unit (MSU) has been extensively used for physical context recognition and for inferring activity of the user.

MSU has been developed by ARCES - Advanced Research Centre on Electronic Systems in collaboration with Ducati Sistemi. It is used to estimate the absolute direction the user carrying the device is looking at, the pitch, the roll and some simple but relevant user activities.

The MSU was designed to be inserted inside a context-aware mobile device called Whyre®, produced by Ducati Sistemi, with the contribution of Intel Labs. The development of this device to support on-site CH exploration was one of the goal of the MUSE (*MUseum and Site Explorer*) project. MUSE was a three years long industrial research project (2001-2003), managed by Ducati Sistemi and founded by MURST (*Ministero dell'Università e della Ricerca Scientifica e Tecnologica*) within the *Italian National Research Program on Cultural Heritage*, PARNASO. MUSE was presented in [Malavasi et al.'00; Salmon et al.'01; Garzotto et al.'03; Muzii et al.'03]. The pilot application for the Museum and Charterhouse of San Martino, (Naples, Italy) was demonstrated during ICHM'O3 [Muzii et al.'03]. The MUSE system has been tested so far by two Italian primary museums and an archaeological site. Research has been conducted to evaluate some relevant aspects of a museum visit using this kind of multimedia guide like [Salmon et al.'04].

Significantly progress has been made since its first release in 2002, with the aim of improving accuracy and precision of the MSU.

3.1.1 Multi-Sensor Unit: characteristics

This section describes the MSU characteristics. In particular the different sensors mounted on the board, their characteristics and the improvement carried out will be described.

3.1.1.1 Whyre

The development of Whyre (Figure 5 and Figure 6) has been one of the main focus of the MUSE project [Salmon et al.'04; Raffa et al.'07b]. Whyre is a hands-free, sensor augmented, context-aware wearable computer. The purpose of Whyre is to act as a guide for cultural sites, hiding the technology from the visitors and making different types of multimedia content accessible through a unified interface [Roffia'04]. Appropriate content is selected based on the user's context, detected by sensors embedded in the mobile device.



Figure 5: Whyre: the device

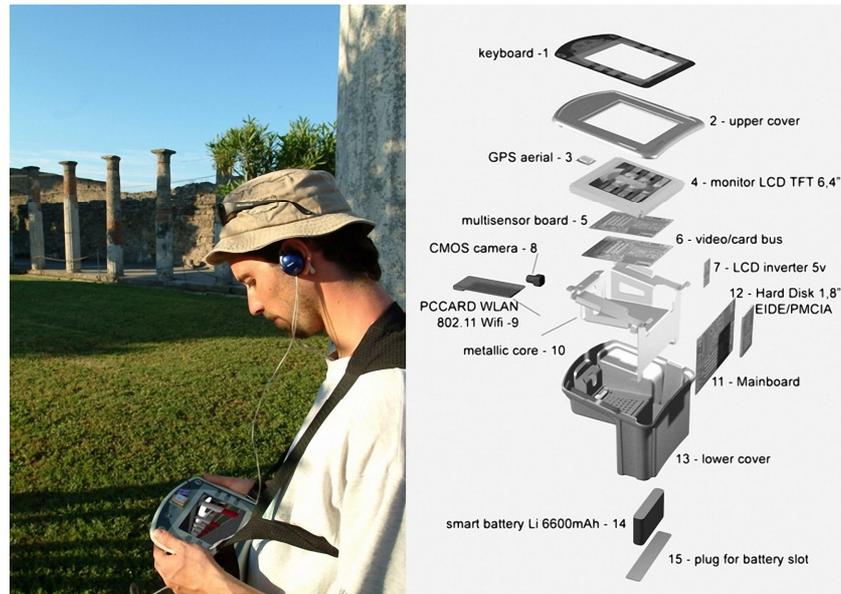


Figure 6: Whyre: use and components

The hardware is conceptually partitioned into three modules:

- The Microprocessor module;
- The Wireless Communication Module (WCM);
- The Sensor module.

The *Microprocessor module* design is based on the system electronics of the Barracuda and Dolphin concept platforms developed by Intel Labs [Raffa'05].

The *wireless communication module (WCM)* is a standard PCcard, allowing it to be either a WLAN or a GPRS module. In the existing pilot installations IEEE802.11b modules are used. In addition, a camera is currently interfaced to the Microprocessor module.

The *sensor module* is embedded in the device. It integrates a combination of inertial and geomagnetic sensors (Figure 7):

- a 2-axis accelerometer by Analog Devices ADXL202 [ADXL202];
- a 1-axis gyroscope by Analog Devices (ADXRS150ABG) [ADXRS150];
- a three bit digital compass by Geosensory (RDCM-802) [RDCM-802];
- a Royaltek GPS module (RGM3000) [Royaltek];
- a low power Texas Instrument microcontroller – MSP430F149IPM [TI].

The firmware of microcontroller implements a data format and a low level fusion algorithm (User Tracking Algorithm), providing the following measurements with a rate of 8Hz:

- Pitch and Roll (from accelerometers) are within a range of $+90^\circ \div -90^\circ$;
- Yaw, $0^\circ \div 360^\circ$, that can be absolute respect to the magnetic North with the use of the compass or relative to the last “Reset” command given by the software;
- Azimuth measurement provided by the compass, in terms of the eight principal compass points;

- Number of Steps, relative to the last “reset” command;
- X, Y in meters, relative to the last “reset” command;
- StepLength, in meters of the last detected step.

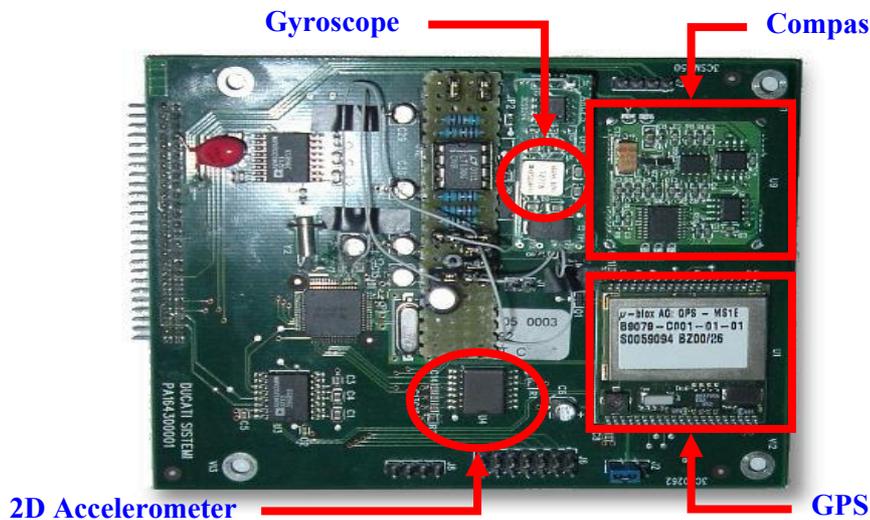


Figure 7: MSU I

The embedded sensors in the Whyre are strongly influenced by the way the device is worn. To maintain the stability during the walk, the unit is placed at the stomach level of the person. In this way the output azimuth corresponds, most of the time, to the line of sight of the direction of walking. The MSU uses only a 2-axis accelerometer and a 1-axis gyroscope, instead of 3D inertial sensors, because this is the simple configuration to obtain a complete 2D trajectory of a walking user.

In the MUSE project the first implemented indoor localization systems was performed using existing WLAN infrastructure, that provided a coarse granularity at room level. The MSU was used to detect the user direction inside each room, visualizing on the device the exhibitions exposed on the wall in front of the user [Raffa'05].

3.1.1.2 Improvement of Multi-Sensor Unit

Extensive experiments with MSU I and Whyre in two different museums highlighted the following problems:

- Error in heading detection: the eight principal directions provided by the compass were subject to hard iron effects that varied their amplitude, depending on the device in which the MSU was mounted;
- Noise of the power supply caused by non regular current absorption of the compass;
- Error of gyroscope output caused by the power supply noise;

- Need to test communication interface and power consumption.

All these aspects together with the will to use the MSU also with other handheld devices, i.e. PDA and smart-phone, pushed the design of a new improved prototype of MSU, called MSU II (Figure 8). No sensors changed, except for the GPS receiver, that has been placed externally from the MSU, gaining useful space. Improvement of MSU II circuit are listed below [Tortoriello'04] :

- Decoupling of the power supply line for analog and digital circuits, using an active power filter;
- Increase of dynamic range by increasing the reference voltage of the A/D converter from 2.5 V to 3.3 V (increase of the scale factor of angular rate).
- Introduction of a voltage follower to separate the signal conditioning stage from the sensing stage (gyroscope).
- Introduction of a RC-low pass filter at 15Hz that filters the gyroscope output signal.
- Introduction of a voltage regulator (the same that produces the reference of the analog to digital converter) to filter power conditioning stage
- Possibility to correct the gyroscope offset, in order to set the best gyro offset.
- Change of the accelerometer filter from 50Hz to 30 Hz.

In order to use the MSU with other types of devices, different adapter modules, supporting wire and wireless communication interfaces, have been implemented. The wire communication interface includes the possibility to communicate using the serial or the USB connection. Wireless connection, characterized by the high flexibility and the low power consumption consists in Bluetooth and the Zigbee interfaces [Roffia et al.'06]. The new MSU has been placed in a wearable box attached to a belt (Figure 9).

In this way the unit is placed at the waist level of the person and the output azimuth will correspond to the walking direction of the user.

Due to an improved MSU-II power management, the new board has also the capability to turn on/off certain sensors according to the current situation, improving the power efficiency. Estimated power consumption of MSU-II is roughly 1800mW with all the sensors switched on. This is an estimation and in “normal” situation, power consumption should be lower, due to the fact that sensors are switched off depending on the user’s context and environment (section 3.1.4).

After MSU II, a new industrial sensor module has been developed by DS with additional features and reduced size, used with a new mobile tourist guide. In MSU III (Figure 10) two sensors have been replaced with newest and more performing ones. In particular:

- the old 3 bit digital compass RDCM-802, has been replaced by a compass of Devantech, CMPS03, based on a magnetometer by Philips KMZ51, that has a 2 degree accuracy [KMZ51];

- the old RGM3000, the GPS of Royaltek, has been replaced by the REB-3310 that gives high performances thanks to the newest SIRF III, instead of SIRF II.

MSU III shows higher performances than the previous releases, due also to a new design in sensor positions that implies a reduction of interferences.

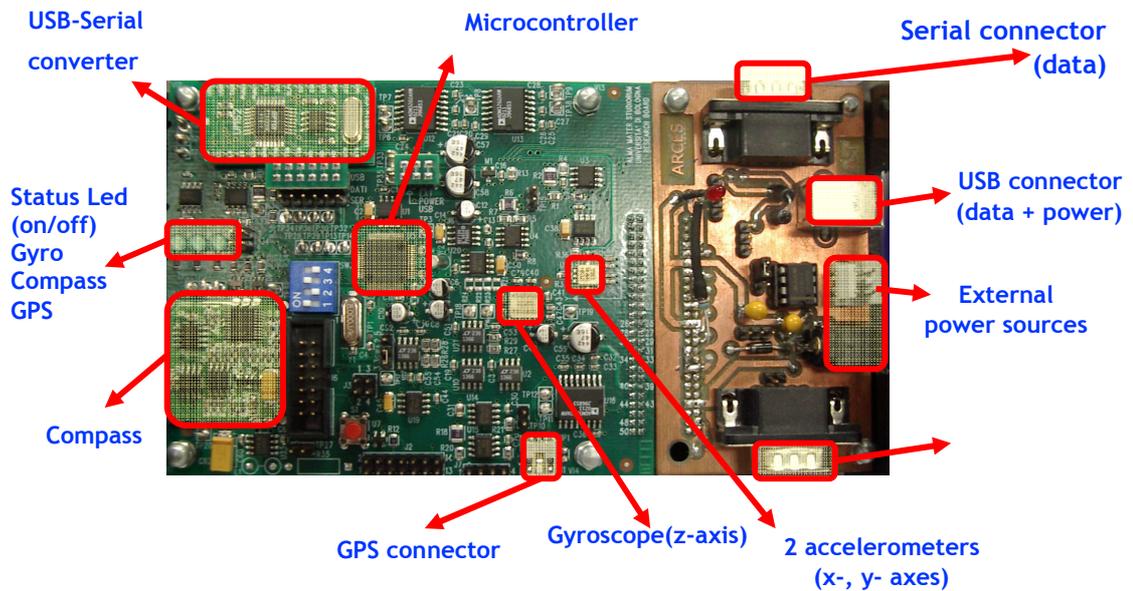


Figure 8: MSU II

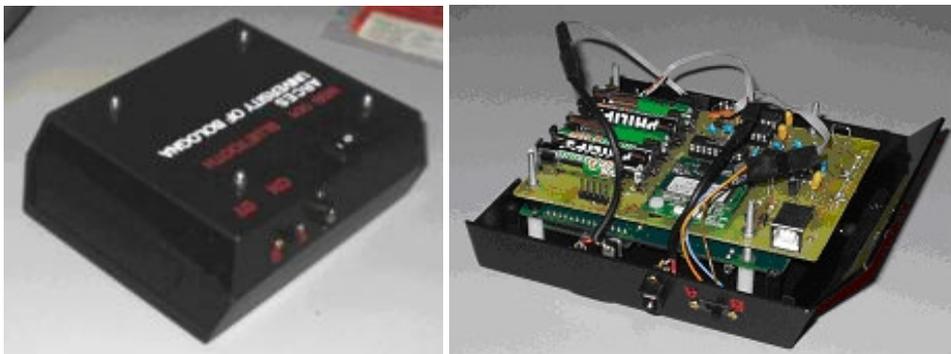


Figure 9: MSU II with Bluetooth connection.



Figure 10. MSU III

3.1.2 Pedestrian Tracking Algorithm

Measurements collected by the MSU are processed in real-time to estimate user position and activity. Based on literature on human walking analysis [Ladetto et al.'00] the PDR algorithm (Figure 11), is able to:

- Estimate the number of steps;
- Estimate the length of each step;
- Evaluate the heading of the walk.

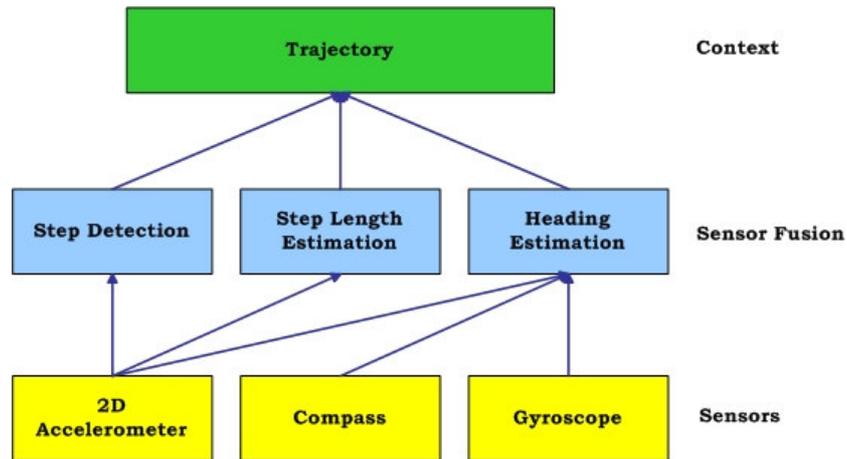


Figure 11: Trajectory detection algorithm

3.1.2.1 Step detection

A cycle of human walking is composed of two phases: standing and walking phase. Detect user's step means recognize the walking phase. The steps are normally detected by analyzing the pattern of the accelerometer signal, that is a function of the board's position on the user's body, the type of movement (going up or down stairs, crawling, running etc.), the ground type (hard or soft surface, sand), the user's physical characteristics and the walking speed

3.1.2.1.1 Algorithm

The developed algorithm considers a normal walk of a pedestrian on a hard surface, i.e. a visitor inside a museum. The 2-axis accelerometer mounted on the board is parallel to the ground. This means that it is able to detect the frontal and lateral acceleration, but not the vertical ones. This particular setting derives from the necessity to compensate the tilt of the 1D gyroscope presents on the board. However, although the accelerometer is approximately parallel to the movement plane, studies conducted in our laboratory prove that the frontal acceleration as a signature is similar to the vertical one. Figure 12 shows the two acceleration pattern during a

gait cycle: each step is characterized by four different peaks: a first positive frontal acceleration peak followed by a positive vertical acceleration one. These are then followed in the same order by two negative acceleration peaks [De Angelis'05].

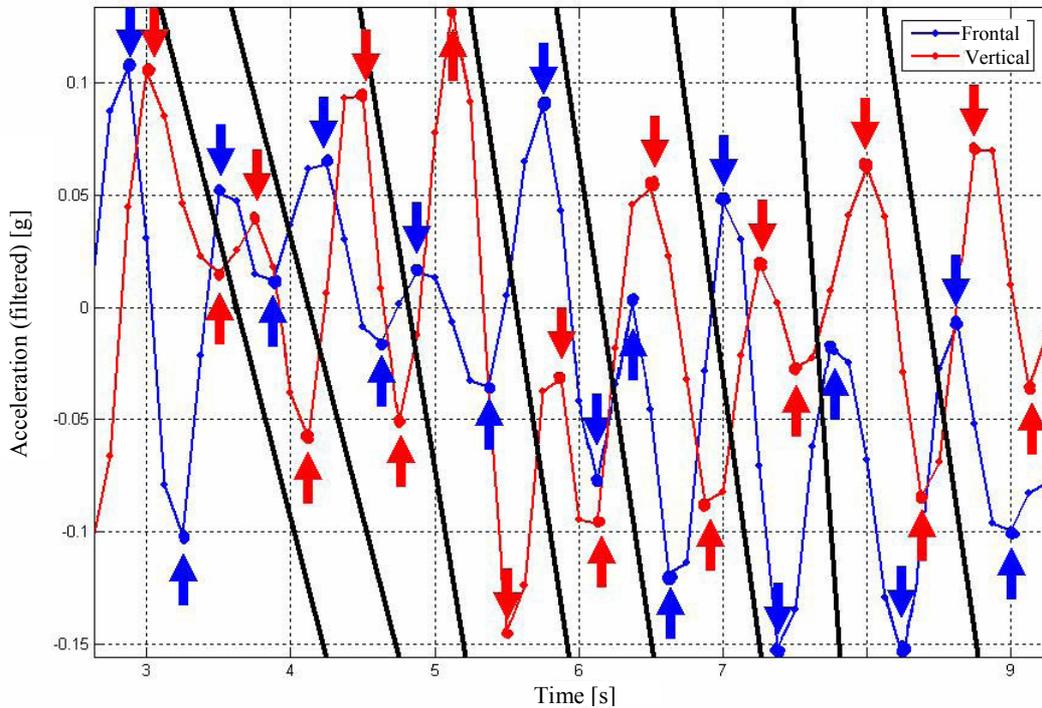


Figure 12: Frontal vs. vertical acceleration

In order to detect a step using our equipment, the algorithm should be able to detect two successive positive and negative frontal acceleration peaks.

As shown also in Figure 13, the frontal acceleration detected during a gait cycle is characterized initially by a positive derivative (green arrow). The end of the step is indeed characterized by a strong negative derivative of the frontal acceleration (red arrow).

A Finite States Machine (FSM) (Figure 14) recognizes the sequence of these two events and detects the step. It has been implemented in the MSU firmware and it is able to provide basic but useful pedestrian activity information, i.e. still or motion.

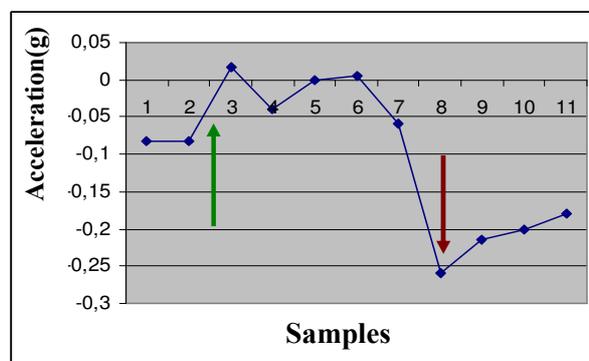


Figure 13: Frontal acceleration during a step

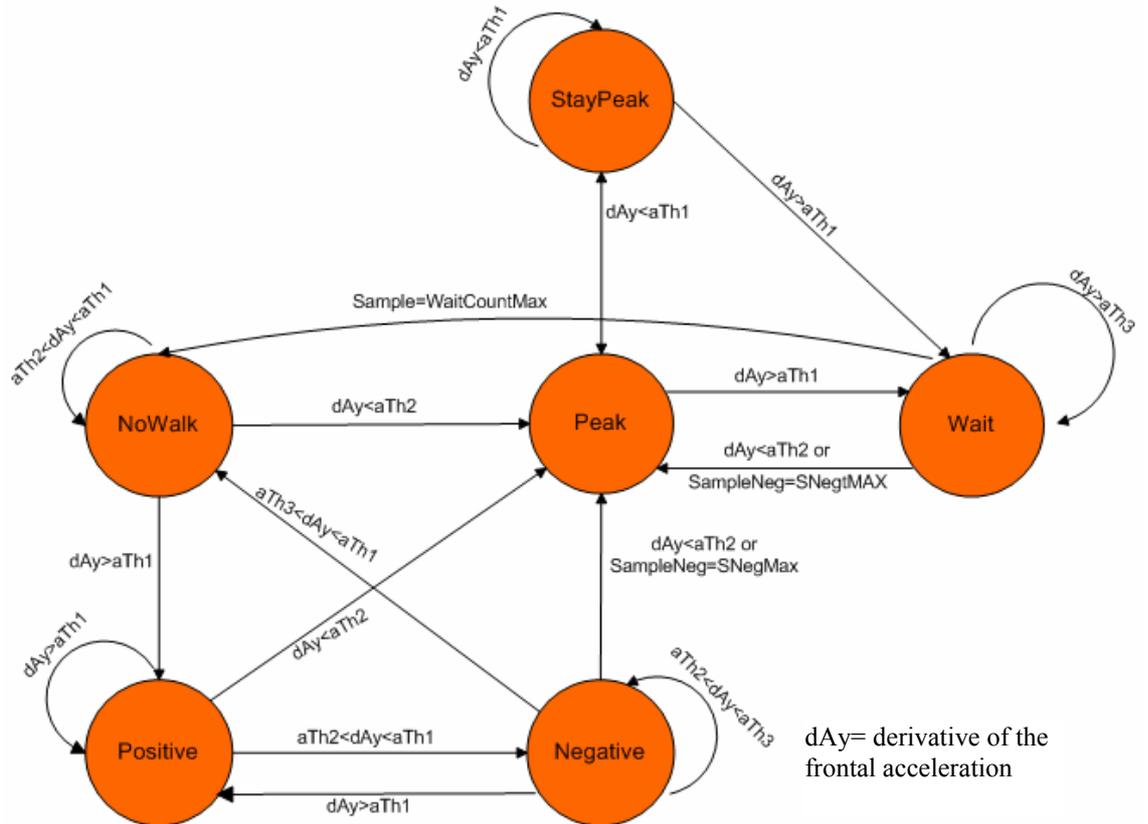


Figure 14: Finite State Machine

The FSM is based on a series of thresholds used to detect positive and negative frontal acceleration peaks that identify each step. Thresholds used in the algorithm are:

- **aTh1** is used with the positive derivative. If dAy is greater than this threshold the FSM detects the step;
- **aTh2** is used with the negative derivative to detect the step;
- **aTh3** is a negative threshold necessary when the negative derivative is not “negative enough”. It is used to detect “slow” steps;
- **WaitCountMax** is the maximum value to assign to the variable **Sample**;
- **SNegMAX** is the maximum value that of counter **SampleNeg**.

The most important variables used in this algorithm are:

- **dAy** is the derivative of frontal acceleration. It is computed by making the difference between two instants. The datum is available every time there is a new sample (8Hz)
- **nCamp** represents the number of samples read every step. When the step is detected **nCamp** is reset.
- **nCampNeg** represents the number of samples for every step with negative derivative.

The FSM maps every important change in the derivative of the acceleration signal into a precise state:

- **NOWALK**: the user is standing still. It is the starting state.
- **POSITIVE**: the derivative acceleration has positive values. It could be the beginning of a step. The FSM remains in this state until the derivative is bigger than the threshold.
- **NEGATIVE**: the derivative acceleration has a negative value. Usually the FSM passes in this state when there are some spurious oscillations.
- **PEAK**: the FSM detects a negative derivative acceleration, that represents the real step determination.
- **STAYPEAK**: the FSM is in this state if the signal presents a negative derivative for more than one sample. The step is detected when the FSM goes out from this state.
- **WAIT**: the FSM waits for a successive step.

3.1.2.1.2 Evaluation and results

The algorithm performance has been evaluated by conducting field tests with different users and different types of walks. From the test results of the PDR algorithm, it can be seen that it is able to detect 90% of the steps done. Despite the result, it is worth noticing that any acceleration relative to the user will cause a distortion in the signal pattern, which may lead to faulty or missed step detection. Thus, the MSU needs to be mounted securely on the user's belt.

Figure 15 shows how the FSM detects user's steps, reporting the frontal acceleration and the state. NOWALK is the starting state, during the walk the machine oscillates between the state PEAK, STAYPEAK and WAIT. The red circle represents the step detection, that occurs when the FSM is in the PEAK state or alternatively when the FSM goes out of the STAYPEAK state.

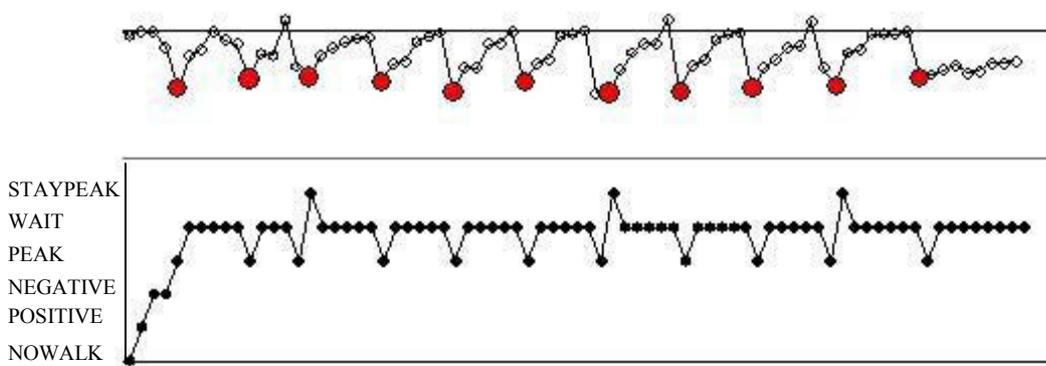


Figure 15: Frontal acceleration and step detection

3.1.2.2 Step length estimation

In order to reconstruct the user's trajectory the length of each step has to be estimated. The step length is defined as a distance between two successive heel impacts [Ladetto'00].

3.1.2.2.1 Algorithm

An intuitive way to measure walked distance is by multiplying the number of detected steps by the average step length. Unfortunately using a fixed value for stride, length will always result inaccurate. In fact the step length does not remain constant and varies depending on the person, walking speed and step frequency. In order to obtain an accurate PDR platform a real-time estimation of step length during the walk is necessary. Figure 16 shows the leg position during a gait cycle. From a mathematical point of view the step length could be estimated by:

$$lengthStep = 2A \sin(\alpha)$$

Despite its simplicity, this formula cannot be used in real applications, because it does not consider other important parameters, i.e. acceleration, velocity and frequency, resulting in an estimation that can vary also of 40% [Zambonelli'05].

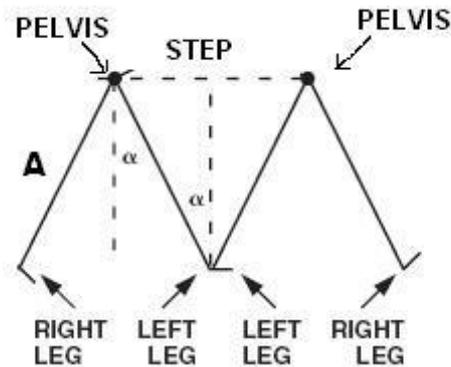


Figure 16: Leg position during a gait cycle

The proposed algorithm estimates the step length as a function of the maximum and minimum acceleration during each step, according to the work reported in [Weinberg'02].

Therefore:

$$StepLength = \alpha^4 \sqrt{accMax - accMin}$$

where α is a constant based on the actual person wearing the MSU device and needs to be calibrated. This is an empirical formula where $accMax$ and $accMin$ refer to vertical acceleration. The proposed algorithm, using the frontal acceleration, instead of the vertical one is able to estimate a precise step length. Although the parameter α is user specific, a mean value $\alpha=0,927$ used to initialize the algorithm has been derived from user studies.

3.1.2.2.2 Evaluation and Results

The experiment reported in Table 2 shows errors of MSU II detected in computing the step length of different person using $\alpha=0,927$, without calibrate the parameter.

User	Real Distance	Estimated distance without calibration ($k=0,927$)	Error
Alessandro	100m	103,74 m	+3,74 %
Daniele	100m	132,35 m	+32,35%
Marina	100m	123,99 m	+23,99 %

Table 2: Distance error

Results show, as expected, that the calibration of parameter α is required to have a better estimation of the traveled distance. Otherwise it is possible to achieve error of 30%. In sections 3.2 and 3.3 two developed methods to improve the step length computation will be described.

3.1.2.3 Heading estimation

The user's direction is computed using measurements gathered from 2-axis accelerometer, 1-axis gyroscope and 2-axis compass, mounted on the MSU, using the general schema shown in Figure 17.

3.1.2.3.1 Algorithm

In the heading detection the 2-axis accelerometer is used as inclinometer and measuring the earth's gravity determines the pitch and roll angles with respect to the horizontal plane. The tilt information is used to compensate both the gyroscope and the compass headings.

The 1-axis gyroscope is mounted in a way that detects the yaw rotation speed, and, if integrated over time, provides the change in angle with respect to an initially known angle. Integration of the gyroscope signal should be limited to short time periods, in order to maintain an approximately constant temperature and avoid the integration error which increases with the number of integrated samples. Usually a compass is use to provide gyro starting direction.

The old digital compass sensor RDCM-802 was able to provide only eight azimuth headings (N, NE, E, ES, S, SW, W and WE) as logic signals. The start and end points of the provided sectors were variable, resulting in inaccurate measurements and therefore also in an accurate gyroscope initialization. This is why it was substituted in the newest release of MSU by the magnetometer by Philips, an analog sensor with an accuracy of 1° . The 2-axis compass module consists of two magnetic sensors that sense two components of the magnetic field. The

azimuth signal provided by the compass is used as initial orientation to determine the absolute direction of the gyroscope.

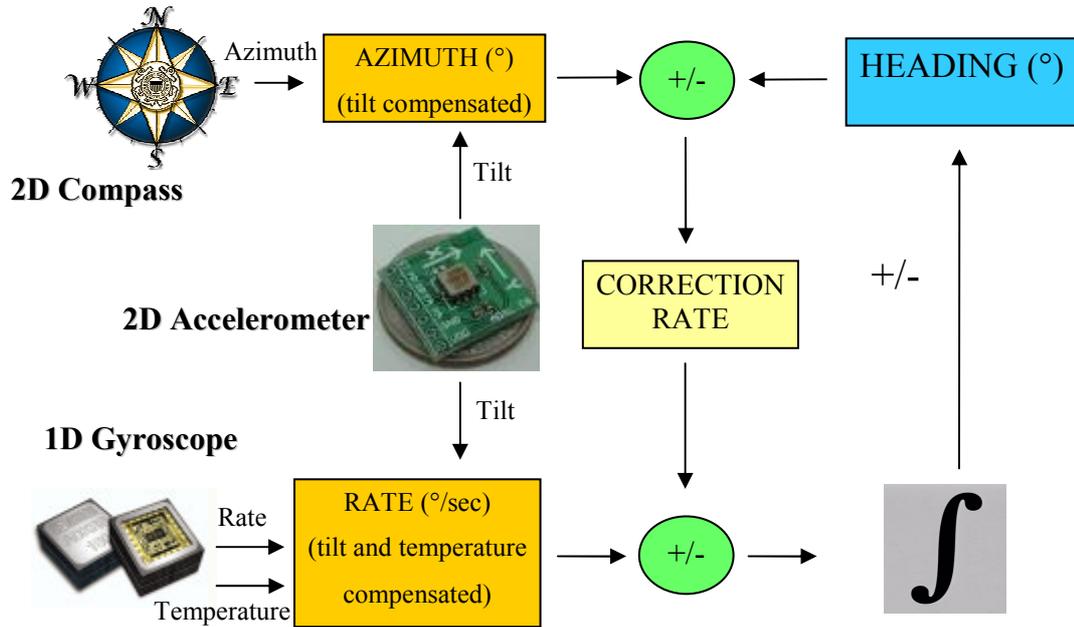


Figure 17: Heading system: conceptual schema

Azimuth determination is however affected by error. Sudden rotations measured by a magnetic compass can be caused either by the movement itself or by a magnetic disturbance. Oscillations of human body in a walking behaviour also cause errors. In order to improve the reliability of the azimuth determination, a combination of the magnetic compass with the gyroscope has been considered, to compensate the drawback of the one with the advantage of the other. Numerous research has been conducted to validate this approach [Ladetto et al.'02].

The general approach used in the integration is that when both gyroscope and magnetic compass data are available, the module will determine the absolute heading by using information from the two sensors. The algorithm will check the presence of magnetic interferences by comparing gyroscope and compass data. If the gyroscope and the compass do not indicate a turn at the same time it means that there is a magnetic perturbation: from this moment the algorithm will consider only the gyroscope for detect the azimuth. In the absence of such disturbances, the continuous measurement of the azimuth allows to estimate and compensate the bias and the scale factor of the gyroscope.

All these approaches have been studied separately by our research group, and they expect to be all integrated in the MSU.

At the moment the algorithm running on the MSU II, the sensing platform used during this thesis, is able to compensate the gyroscope with the 2-axis accelerometer and does not use the compass. For this reason the proposed research attempts to exploit external localization system to provide the starting direction of the gyroscope.

3.1.2.3.2 Evaluation and Results

Experiments conducted in the archeological site of Pompeii using the MSU II without the compass, show different errors, that are more understandable if compared with the trajectory detected by the GPS, that in this case is not affected by error.

In this experiment the initial heading information has been set manually, knowing the exact direction.

Results (Figure 18) show that the dead reckoning tracking (red path) is smoother than the GSP trajectory (green path), but it suffers from the following inaccuracies:

- The heading drift after a long walk on a rough and bumpy path (Figure 18: segment “B”).
- The number of steps and the step length (Figure 18: segment “A”);

Figure 18 shows an accumulated heading drift of 12 degrees and an average 7% error in the path length measured and after a 200 m walk (approximate walking time: 215 sec).

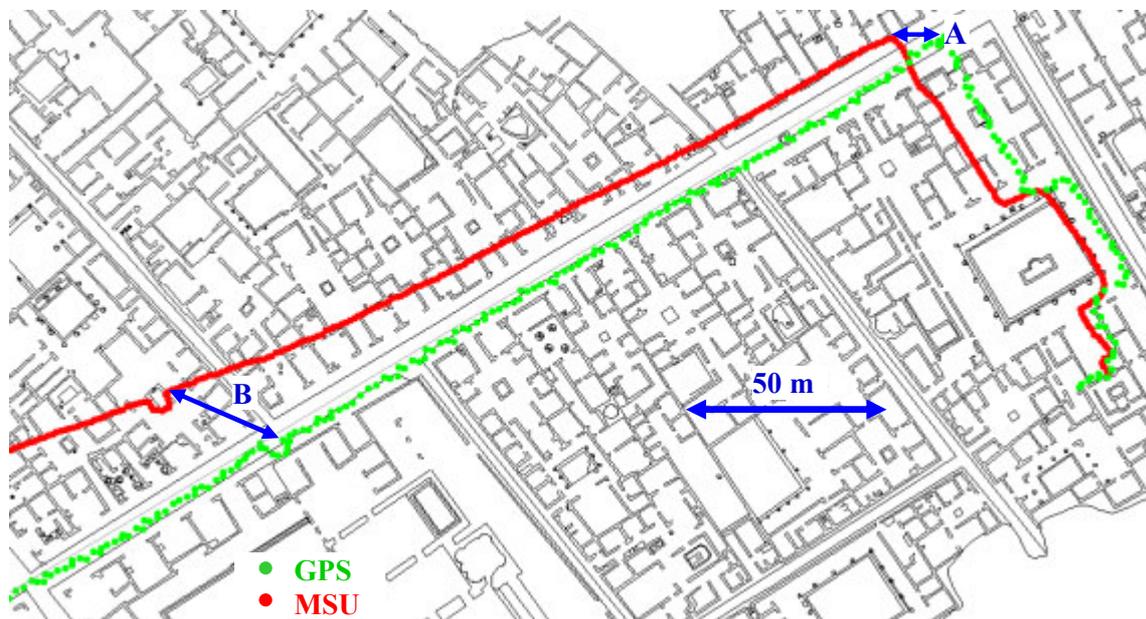


Figure 18: MSU compared with GPS

3.1.3 Conclusions

The dead reckoning system presented in this section may be useful where external infrastructures cannot be installed, but it requires to be periodically resynchronized. For this reason, an “absolute” system should be combined with the MSU.

In the next sections two approaches to increment the accuracy of MSU will be presented. The goal of this research is to provide a smooth tracking of user location, regardless of the continuous availability of absolute systems based on external sensors.

3.2 Dead reckoning supports stereo vision in pedestrian navigation

The proposed system is a novel hybrid approach to localization; it combines the *Pedestrian Dead Reckoning System* (PDRS) describe in the previous chapter with a *Stereo Vision based Tracking System* (VTS). Developed systems provide personal positioning usually making use of self-contained sensors and wearable camera [Lang et al.'02; Masakatsu et al.'03; Bay et al.'05]. The proposed approach, on the contrary exploits a stereo camera installed in the environment.

The *PDRS*, presented in previous section, is a navigation system available on mobile visitor guides. In this implementation we used the Whyre device with the MSU II (switching off the compass). The *VTS*, developed by the Computer Vision Lab of the University of Bologna, (section 3.2.1), is a server centric application that tracks in real-time user positions from video sequences taken by a stereo camera. The position of visitors is used also to monitor and gather statistical data about the flow of visitors.

Section 3.2.2 describes how location information gathered by the *VTS* is used by the *PDRS* to calibrate the mobile guide's initial position and navigation parameters. The resulting location system enables mobile guides to provide more fine granularity context-aware services and content, improving the experience of the visitor.

3.2.1 Stereo Vision based Tracking System

The capability to visually track several moving persons over long time spans through occlusions and across complex backgrounds represents a crucial and still largely unresolved issue. Many methods for real-time multi-person detection and tracking based on the analysis of images supplied by a static camera have been described in the literature.

Unfortunately, due to the overlapping of people in the 2D images as well as to rapid changes in their appearance it is extremely difficult to robustly maintain tracks integrity over time. On the other hand, 3D scene reconstruction using stereo cameras holds the potential for dealing with these issues. In fact, yielding the 3D coordinates of image points, stereo allows to build an orthographic view of the scene with the projection plane parallel to the ground plane. In such a projection plane people tend not to overlap significantly and their appearance cannot change quickly. An orthographic view that has proven to be very effective for reliable multi-person detection and tracking can be obtained by means of plan-view statistics, i.e. occupancy and height maps [Beymer'00; Harville'04]. The Visual Tracking System used in this research is based on the concept of plan-view statistics and deploys a down-looking digital stereo camera,

i.e. an STH-MD1 by VIDERE DESIGN mounted overhead at a height of approximately 3 m from the ground (Figure 19).

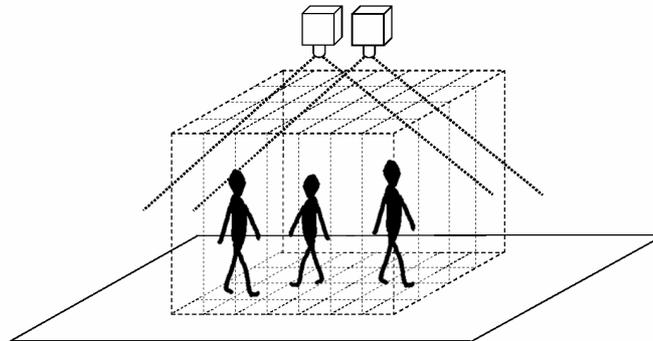


Figure 19: Tracking system with stereo vision

Synchronized image pairs coming from the cameras are first processed by means of a real-time correlation-based stereo matching algorithm [Di Stefano et al.'02] in order to continuously gather dense disparity maps. Since the stereo camera is fully calibrated, the disparity information associated with each pixel is converted into 3D coordinates with respect to the ground reference frame. Then, a 2D orthographic view of the scene is built by projection of the 3D coordinates associated with moving persons into the occupancy and height maps. People tracking takes place in the 2D orthographic view and relies on Kalman filtering to predict the new positions of tracked objects. An effective heuristic handles in a coherent and straightforward way complex events such as dynamic/static partial or total occlusion and the general case of multiple people merging. Inputs to the tracking algorithm are the list of tracked persons until time $t-1$ and the current set of objects detected within the 2D view at time t . Each entity (tracked person or new object) has a bounding-box located at its centre of mass. Based on the Kalman filter, at time t the algorithm considers the intersections among the predicted bounding-boxes of tracked persons and the bounding-boxes associated with the currently detected objects. The simple case of a one-to-one correspondence between a tracked person and a new object is solved by matching the current object with its associated person (this is called straightforward tracking). When two or more predicted bounding boxes fall onto the same detected object the algorithm assigns the pixels in the 2D view to the objects adopting a distance-based cost function that enforces the following principles:

- The size of people cannot change rapidly;
- The head of people cannot overlap in the 2D view;
- The merged blob must be partitioned among objects keeping the resulting individual objects as compact as possible. A near-optimal solution of the resulting NP-hard problem can be found using an approach based on Lagrangian relaxation. Novel objects appearing in the scene

are firstly compared with recently lost objects: if a match is found then the algorithm assigns the identity of the object otherwise a new people entity will be instantiated.

Experimental results have demonstrated the robustness, the accuracy, i.e. objects are located with an uncertainty of 5 cm * 5 cm at the ground and the real-time performance of the proposed Visual Tracking System.



Figure 20: Stereo-Vision System interface

So user trajectories are evaluated in real-time, frame by frame, and are expressed as timed sequences of locations. Tracked persons are not identified, therefore each trajectory is “anonymous”. For certain services, e.g.: statistics gathering and visitor counting, this feature intrinsically meets the privacy requirements, but it is an obstacle when the visitor carries a mobile guide that needs to be recognized for personalized services (see section 3.2.2).

An important VTS feature is its ability to count how many people cross a virtual line defined in its field-of-view (the green line in Figure 20). The counter values are stored in

MobiComp as time-stamped context elements, and they can be easily re-used by other software modules to provide application specific services.

3.2.2 Pedestrian Dead Reckoning Calibration

The proposed combined localization system uses the PDRS to provide user tracking information, filling the gaps between the areas covered by the high precision VTS. Such an approach is already well-known in different settings where other absolute positioning systems are used instead of the VTS, i.e. GPS. Considering a museum environment the VTS is needed where the density of the exhibits is high and the localization requirements are extremely strict. In areas where the requirements are less strict or where environmental sensors are difficult to be placed, the PDRS may be well suited.

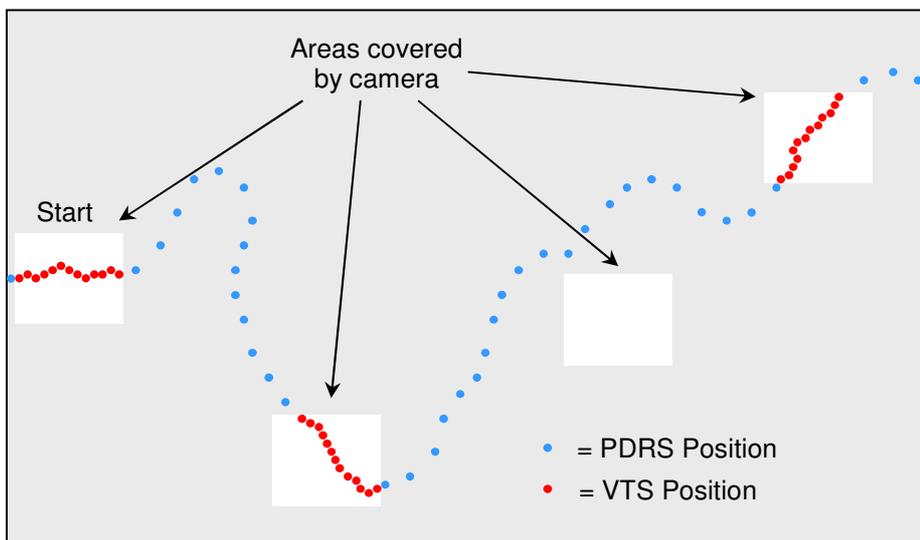


Figure 21: VTS-PDR Localization System

Location is provided alternatively by the VTS and by the PDRS according to the following rule: when both the PDRS and the VTS produce position information, priority is given to the VTS due to its absolute and more accurate data. When the VTS loses track of the user because he leaves its field-of-view, location is provided by the device's PDRS, after being resynchronized with the last position detected by the VTS (Figure 21). The mobile guide relies on the VTS to set its initial position, to fine tune some user dependent parameters, i.e. user gait, and to compensate the inherently growing position error.

At least one stereo camera is required to provide the mobile device with its initial position; additional stereo cameras may be added to resynchronize the PDRS along the visit path as shown in Figure 21. In this way each stereo camera should not only track and count

anonymously all visitors walking under its field-of-view, but also needs to uniquely identify and resynchronize mobile devices.

This section describes how the VTS can be used to improve the accuracy of the PDRS, reporting the implemented algorithms and the experiments conducted, considering a single user situation. The multi-user approach and the algorithm proposed to handle this condition are described in section 3.2.3.

3.2.2.1 Position Initialization

The dead reckoning system is affected by a position error. This error is caused by the wrong estimation of step length. The VTS position information can be used to reduce this error.

3.2.2.1.1 Algorithm

The initialization of the PDRS position is performed when the user is exiting from the area covered by the camera, using the last coordinates estimated by the VTS. In this way it is possible to cancel the error Δ_2 (Figure 22) accumulated by the PDRS. Figure 22 shows that the heading error of the PDRS is not corrected by this approach, resulting in errors Δ_3 and Δ_4 .

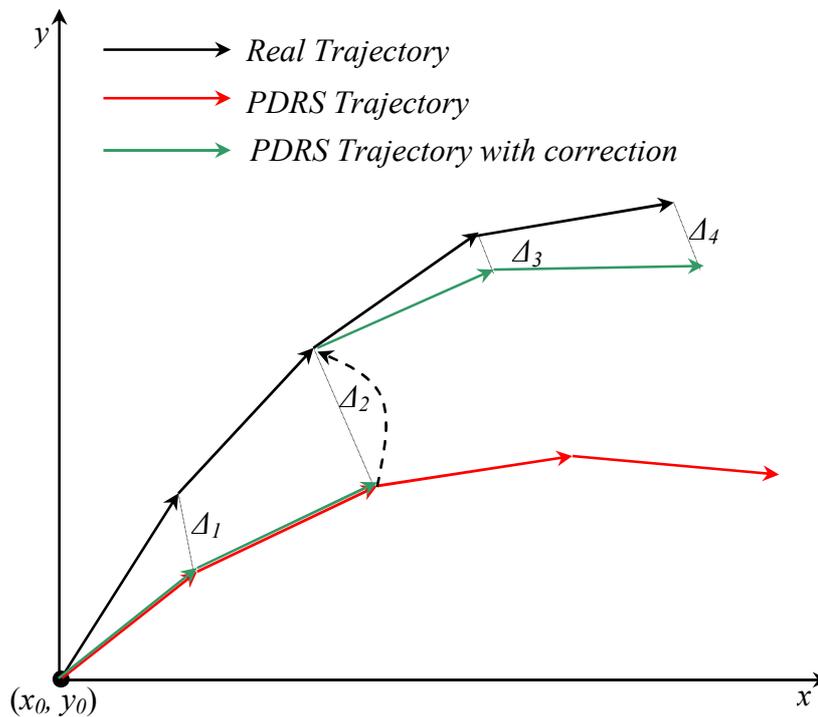


Figure 22: Position correction

3.2.2.1.2 Evaluation and Results

Experiments conducted in the laboratory (Figure 23) show an error of PDRS of about 5% on the total trajectory of 17 meters (red trajectory). Correcting the user position as describe above the accuracy of the user position increases, obtaining an error of 1% (green trajectory).

In general the error associated to the PDRS is not predictable, and depends on various factor, namely the last calibration time, gyroscope saturation problems, etc.

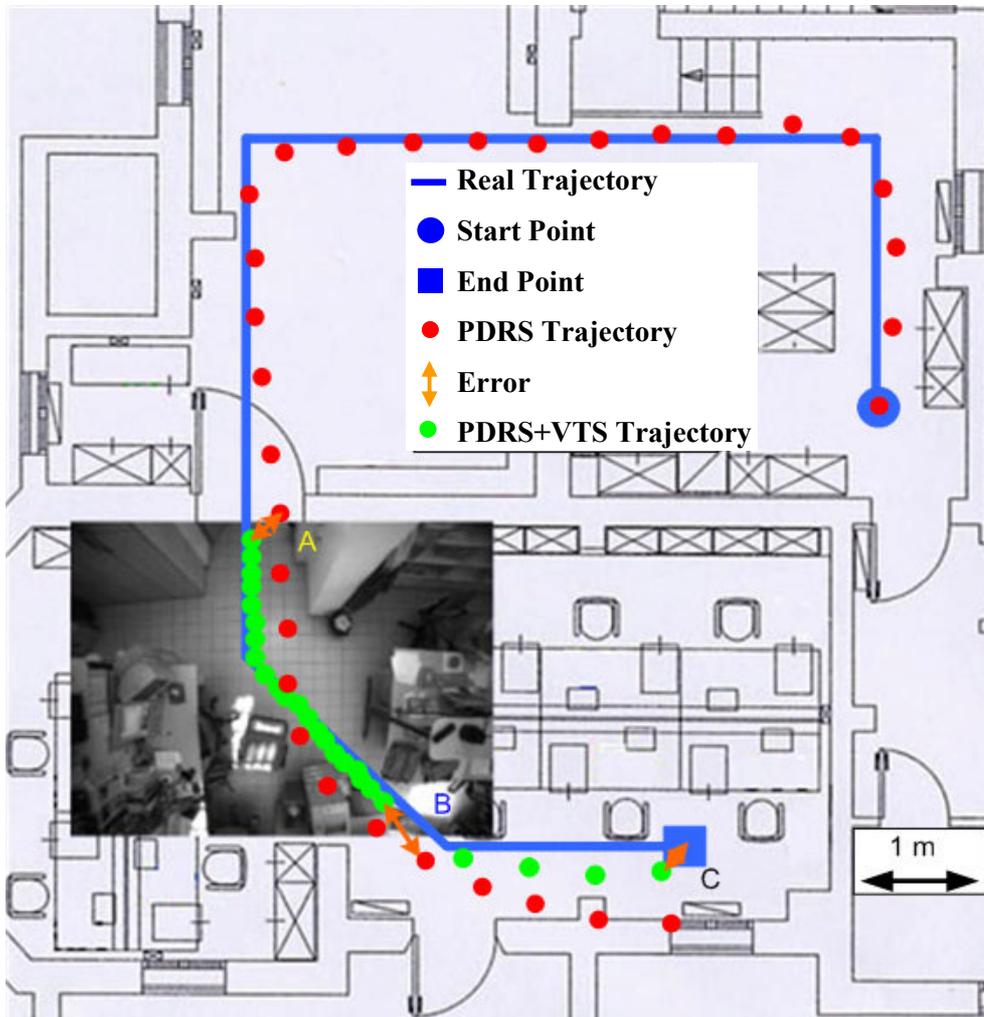


Figure 23: PDRS position correction

3.2.2.2 Step Length Calibration

VTS measurements can be used to estimate the parameter α , necessary to compute the step length (section 3.1.3.2).

3.2.2.2.1 Algorithm

The developed algorithm is based on a comparison between the step length estimated by the PDRS and the step length estimating using VTS position.

When the user is in the field-of-view of the camera, for every step detected by the PDRS, the algorithm estimates the VTS step length, by considering the VTS position in the same instant in which the PDRS detects a new step. In this way, when two successive steps are detected the system estimates the VTS step length.

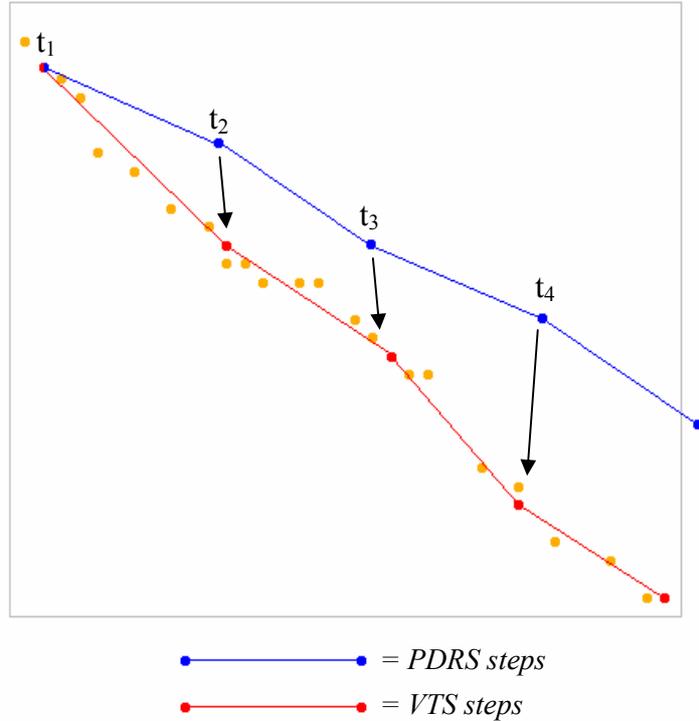


Figure 24: PDRS and VTS steps

An example is shown in Figure 24. The rectangle with the grey border is the area covered by the stereo: blue points are positions provided by the PDRS, orange points are positions provided by VTS and the red point are position provided by the VTS in the step detection instant of PDRS. In order to estimate the parameter α , the algorithm compares the step length detected by PDRS with step length detected by VTS, computing the mean value of the ratio between the two measurements. When the VTS does not detect anymore the user the system updates the parameter α .

At starting time the parameter α is equal to $\alpha_{NEW}=0,927$; whereupon, every time the user walks under the camera, the system updates the value using the following formula:

$$\alpha_{NEW} = \alpha_{PREVIOUS} \cdot \frac{1}{n} \sum_{i=1}^n \frac{L_{VTSi}}{L_{PDRSi}},$$

where L_{VTSi} and L_{PDRSi} are the step lengths detected by respectively VTS and PDRS and n is the total number of steps.

3.2.2.2.2 Evaluation and Results

The proposed approach improves the accuracy of the system, as reported in the following experiments. The mean value of α for different users is reported below (Table 3).

Table 4 and Table 5 show that the accuracy of MSU position can be increase by performing a continuous calibration of user specific parameters.

User	Mean value of α
Alessandro	0,900
Daniele	0,689
Marina	0,756

Table 3: Estimated α value

User	Real Distance	Estimated distance without calibration ($k=0,927$)	Error	Estimated distance with calibration	Error
Alessandro	100 m	103,74 m	+3,74 %	100,72 m	+0,72 %
Daniele	100 m	132,35 m	+32,35%	98,34	-1,66 %
Marina	100 m	123,99 m	+23,99 %	101,12 m	+1,12 %

Table 4: Estimated distance with calibration

User	Real step length	Step length without calibration ($k=0,927$)	Error	Step length with calibration	Error
Alessandro	70 cm	74,8 cm	+6,86 %	72,6 cm	+3,71 %
Daniele	70 cm	85,8 cm	+22,6 %	63,8 cm	-8,86 %
Marina	70 cm	87,2 cm	+24,6 %	71,1 cm	+1,57 %

Table 5: Estimated distance without and with calibration

3.2.2.3 Heading Initialization and Correction

As explained below, MSU II, the platform used in this research, was suffering from an inaccurate compass, that was therefore switched off. This section describes the algorithm used to initialize and correct the gyroscope heading.

3.2.2.3.1 Algorithm

The implemented algorithm considers all the positions provided by the VTS in the interval of two consecutive steps detected by the PDRS and estimates the direction in time of

this set of points, by applying the Least Square Orthogonal Distance method. Basically it consists of:

1. Computing the barycenter of the set of points;
2. Computing the parametric equation which passes for the barycenter;
3. Estimating the line that minimizes the sum of the squared distances.

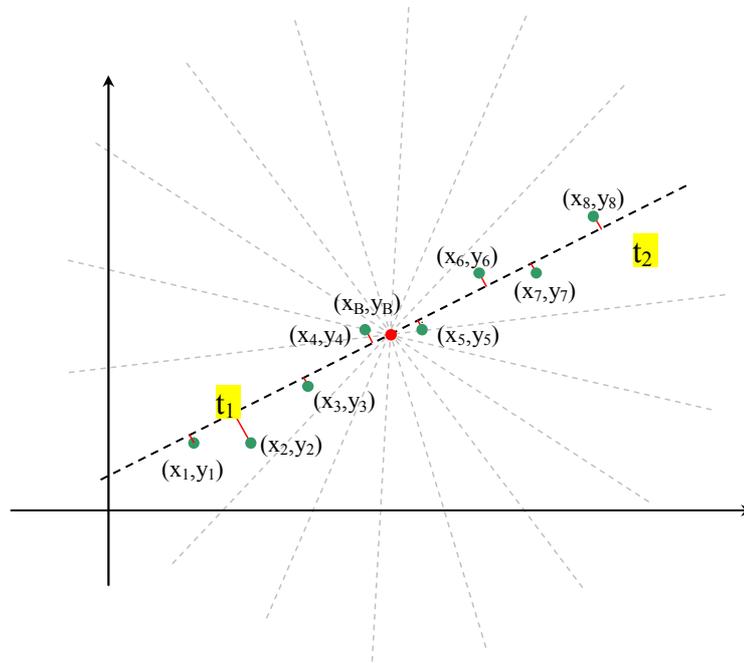


Figure 25: Least Square Orthogonal Distance

The VTS heading estimation is performed when people walk straight sections. A trajectory is defined straight if the difference in degree between the current and the previous step is less than 7° degrees. The threshold has been estimated in real straight trajectories, computing the mean direction error of the gyroscope.

In order to align the gyroscope, the algorithm checks if the user is walking straight, and if this condition is met, the algorithm computes the difference between the PDRS direction and the VTS direction. The heading correction is performed only if the difference between the two direction is bigger than 15° (an estimated threshold that avoids unnecessary corrections).

3.2.2.3.2 Evaluation and Results

Figure 26 shows an example of error in PDRS estimated direction. In this case the system is affected by an error of about 35° . Combining the heading and the position correction, the overall system greatly improves its accuracy (Figure 27).

A second experiment is reported in Figure 28 and Figure 29. The user enters the area cover by the camera with a direction of 90° and an error of 50° , resulting in an estimated direction of 40° . The direction estimated by the VTS is $94,59^\circ$, that even if is not the exact direction (difference of $4,59^\circ$) it can be used to reduce the PDRS error.

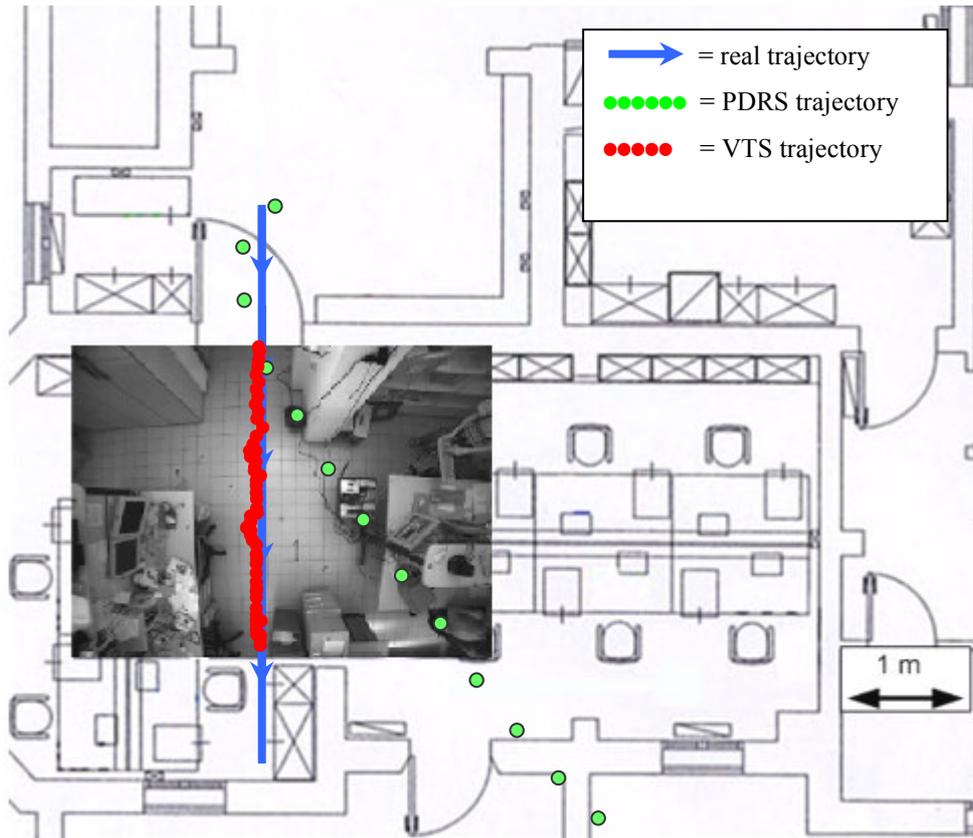


Figure 26: Direction error (1)

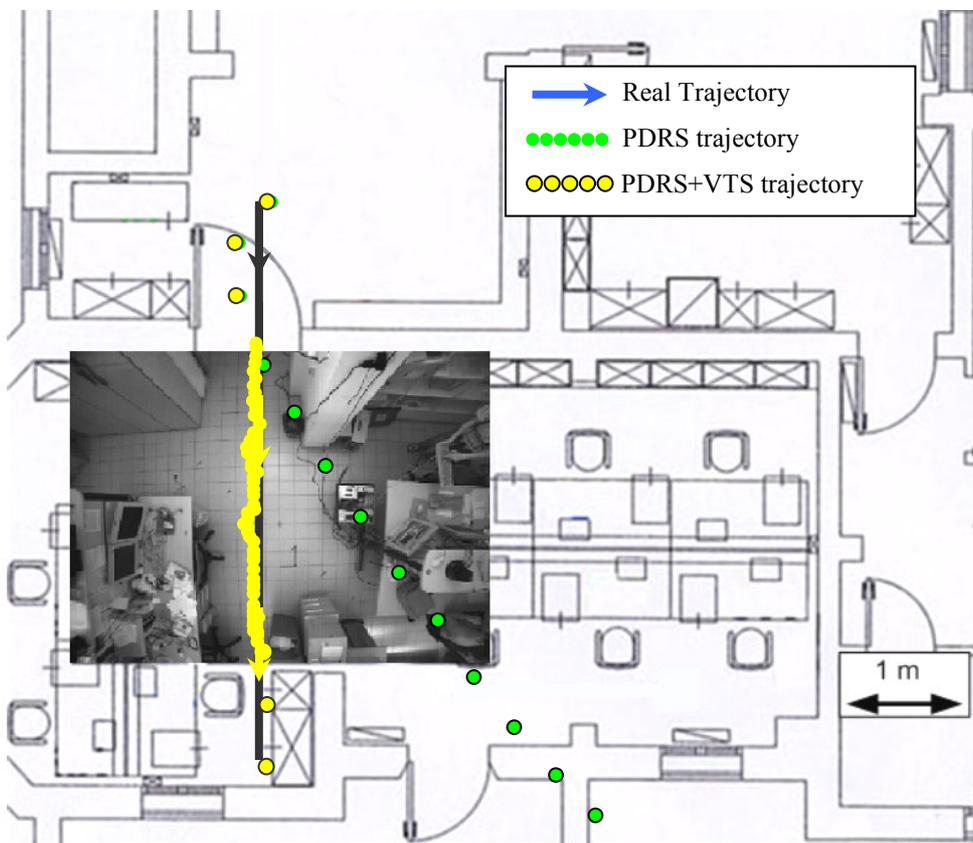


Figure 27: Correction of PDRS direction (1)

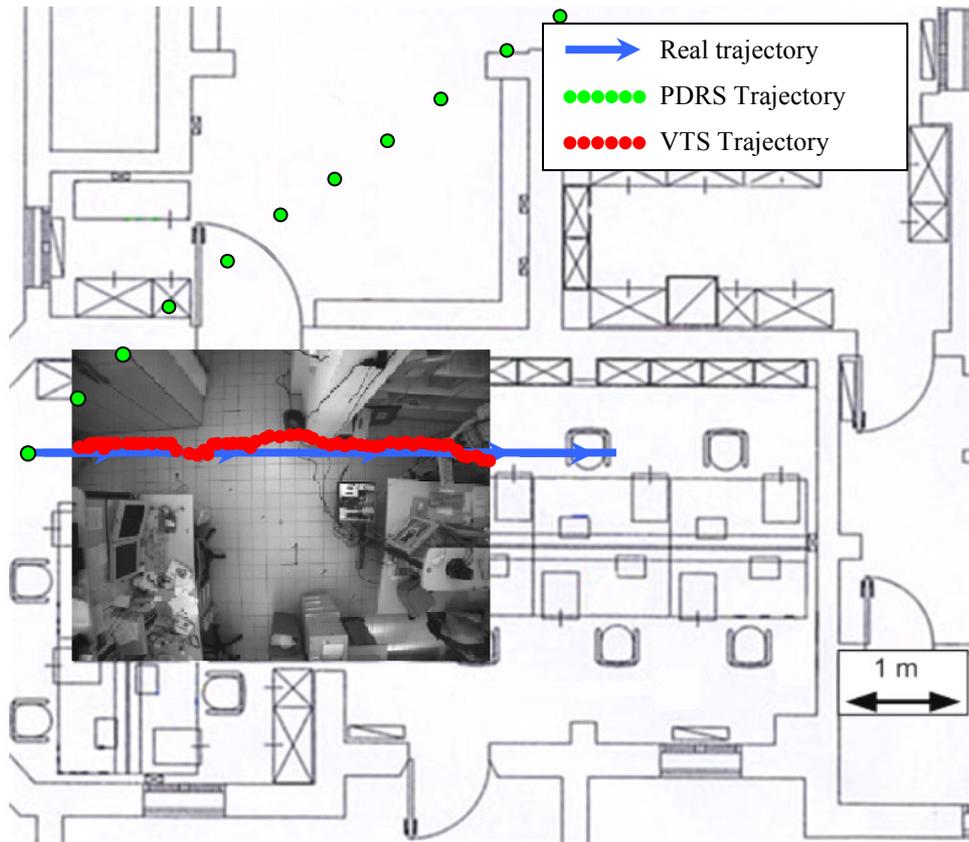


Figure 28: Direction error (2)

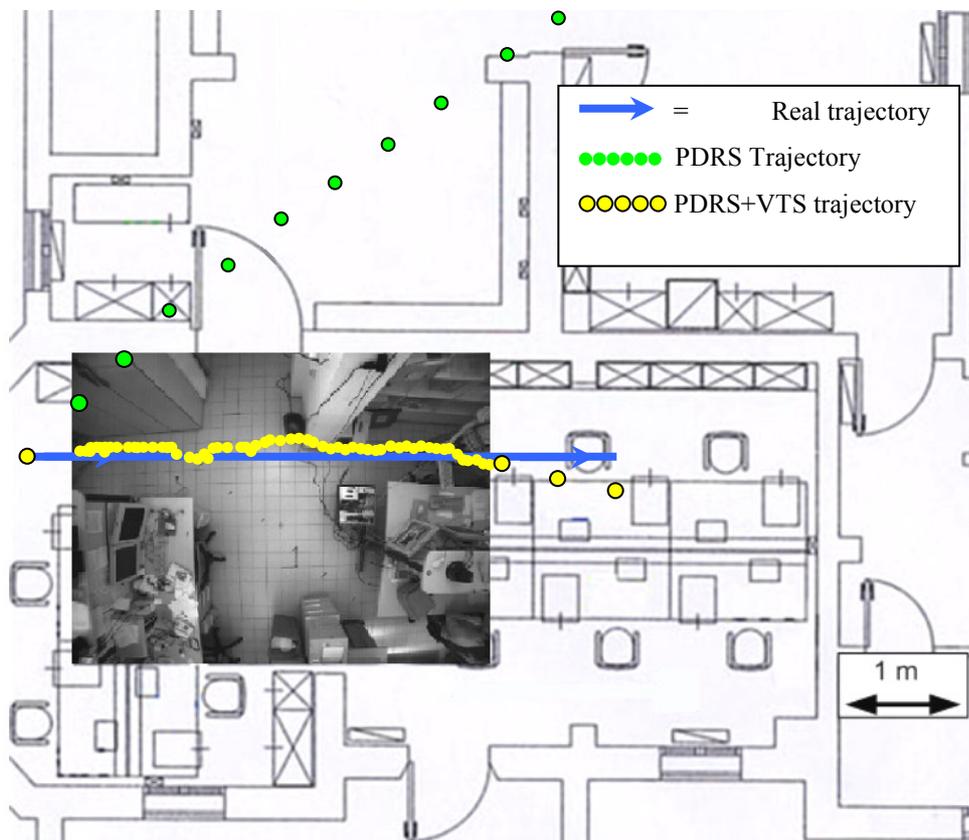


Figure 29: Correction of PDRS direction (2)

3.2.3 Time synchronization considerations

Time synchronization is a critical piece of infrastructure for any system that integrates more sensors with different timing. The discussed system makes use of two different subsystems from which data are gathered using two different sampling rate.

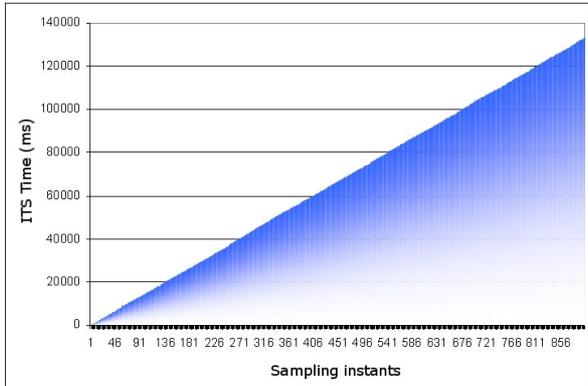


Figure 30: PDRS sampling time

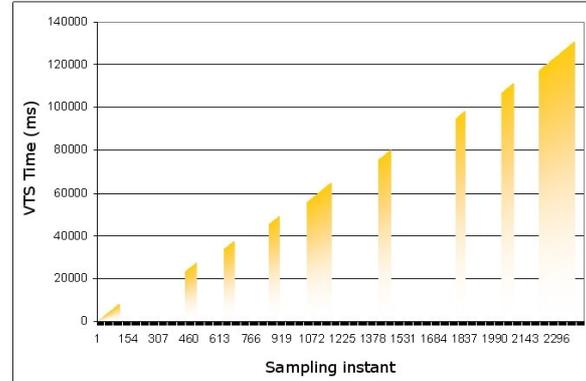


Figure 31: VTS sampling time

Figure 30 and Figure 31 report sampling instants of the VTS and the PDRS. VTS data flow is discontinuous, because it depends on the moving objects detected under the camera: if no person is detected, no position information is sent. On the contrary, measurement data of PDRS are provided continuously at a rate of 8 Hz.

The time difference between the newest available measurement of VTS and the newest available measurement of PDRS is:

- Average time error $|\Delta_{PDRS-VTS}| = 39,00$ ms;
- Standard deviation time error $|\Delta_{PDRS-VTS}| = 29,23$ ms.

The computed errors are referred to a situation in which the two system are initially synchronized. The average time error of 39 ms is equal of an average spatial error of 4cm, conjecturing a user speed of 1 m/s. The error is considered acceptable, because the minimum error of the VTS is equal to 5 cm.

3.2.4 Multi User Identification

Switch between VTS and PDRS associating an unambiguous identifier (ID) to each detected user is one of the major issue to be solved by the proposed tracking approach. The user that moves in and out of an area covered by the camera has to be continuously recognized with an univocal ID known by the two systems, in order to initialize and calibrate the PDRS. The VTS already manages several users, associating to each one an impersonal sequential identity. This ID has to be related to a unique device identifier (e.g. MAC, IP) known by the PDRS.

During this research work several server based approaches for automatic identification of the tracked people have been investigated.

The first one assumes that the mobile device knows the map of the environment, sending its DR position to the server only when it expects to be close to the area monitored by the camera. The problem of this approach is mainly related to the fact that MSU could be inaccurate in computing position after a long time, and could be not able to detect that it is near the area covered by the camera.

A second solution identifies the device to be associated, by computing similarity of the trajectory directions. Even if this solution is better than the previous one, it could be computational heavy, due to the fact that it needs to constantly compare all the trajectories detected by the camera with all the trajectories detected by the different PDR platforms. Due to limitations of these approaches, currently a third solution based on the explicit user request has been developed and described in section 3.2.3.1.

An alternative solution, that has not been implemented till now, is based on use of identifiable markers embedded in the wearable platform. This solution requires strict constrains in environment light to enable the detection of the markers that could be attached on the device or on the user.

3.2.4.1 Matching between trajectories

To associate the mobile target detected by the VTS with the corresponding PDR device, the most easy and intuitive approach consists in computing the position difference between the two trajectories in the same time interval. This solution however is not suitable, because of the intrinsic error of the PDRS, that could result in inaccurate position estimation. The proposed approach takes advantages from the knowledge of the heading direction.

3.2.4.1.1 Algorithm

The algorithm uses the direction difference between the heading direction of PDRS and the heading direction of the VTS. This approach is based on the assumption that gyroscope measurements, even if affected by errors, are stable in the short term. Every time the PDRS detects a new step, the algorithm computes the difference between the variation in time of the two directions.

$$\text{Diff}(t) = \Delta \text{dir}_{\text{MSU}}(t) - \Delta \text{dir}_{\text{VTS}}(t)$$

where:

$$\Delta \text{dir}_{\text{MSU}}(t) = \text{dir}_{\text{MSU}}(t) - \text{dir}_{\text{MSU}}(t-1)$$

$$\Delta \text{dir}_{\text{VTS}}(t) = \text{dir}_{\text{VTS}}(t) - \text{dir}_{\text{VTS}}(t-1)$$

and dir_{VTS} is computed according to section 3.2.2.3.

3.2.4.1.2 Evaluation and Results

An off-line experiment has been conducted to test the feasibility of this approach, using the Whyre equipped with the MSU II.

Figure 32 and Figure 33 report the two different trajectories detected by the VTS and PDRS when the user walks under the camera. Figure 34 and Figure 35 show the difference functions computed considering simultaneous heading variation of MSU and VTS. Table 6 reports the mean value and the standard deviation of all the computed functions. If two trajectories are far apart or they are only close at some directions, the mean value and in particular the standard deviation will be high. On the contrary, similar trajectories show low mean value and low standard deviation. Table 6 (blew row) shows a particular case (*PDRS b – VTS b*) in which the exact association is not characterized by the lowest mean value, but by the lowest standard deviation.

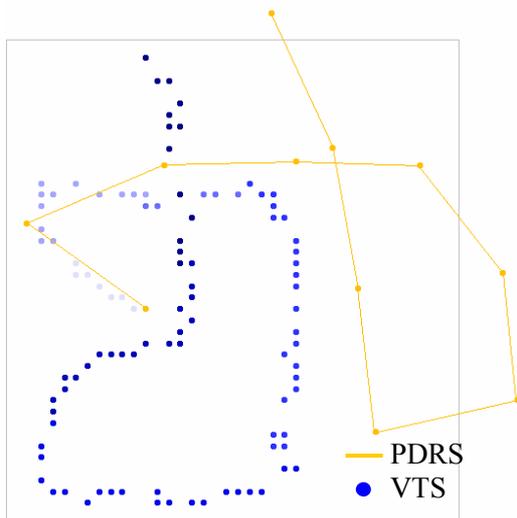


Figure 32: Experiment (a)

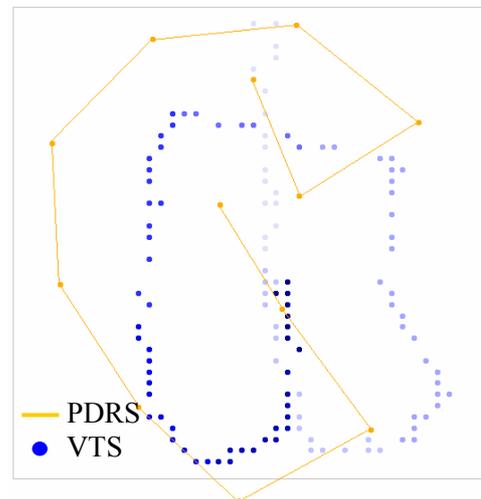


Figure 33: Experiment (b)

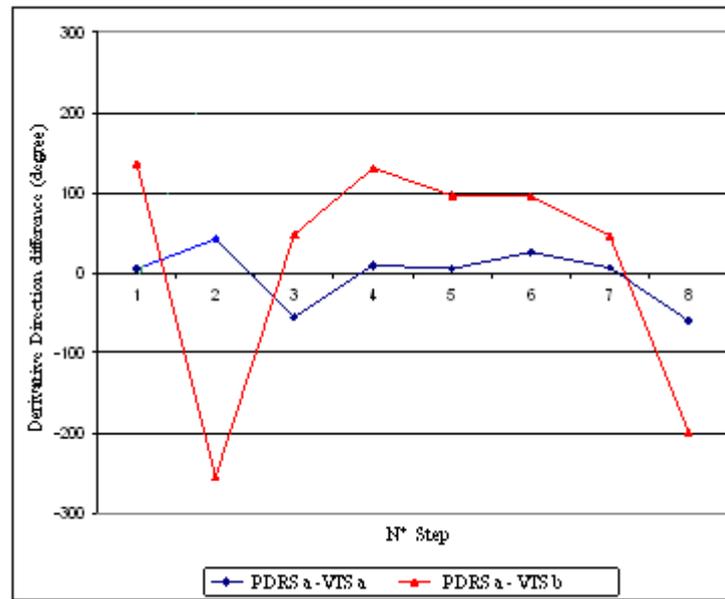


Figure 34: Difference between PDRS and VTS derivative direction (1)

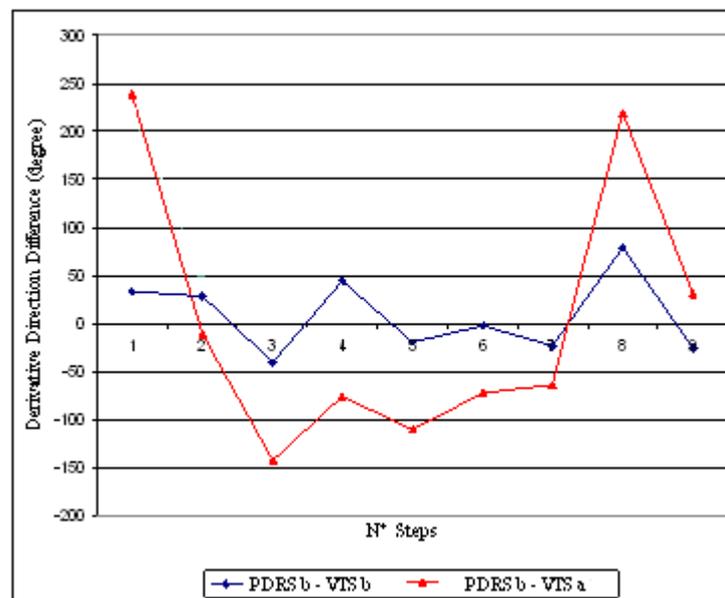


Figure 35: Difference between PDRS and VTS derivative direction (2)

	<i>Mean Value</i>	<i>Standard deviation</i>
<i>PDRS a – VTS a</i>	-2	36
<i>PDRS a – VTS b</i>	12	152
<i>PDRS b – VTS a</i>	1	138
<i>PDRS b – VTS b</i>	8	40

Table 6: Mean Value and STD of the difference function

3.2.4.2 Pre -Identification technique

The need to have a reliable system, even if not fully automatic, driven the realization of an alternative solution, based on the predefined knowledge of some “recalibration areas” monitored by cameras. In order to overcome the not trivial association problem, a semiautomatic approach that leaves the activation of the association to the user has been implemented. With this semiautomatic approach, the error accumulated by the PDRS does not affect the reliability of the association between the device and its trajectory identified by the VTS. During the initial startup of the tour, the visitor has to go under the camera, over an area called “tile” (Figure 36) and press the recalibration key on the mobile guide. When the camera receives the request, it controls if someone is over the area, performs the association and initializes the MSU with the right position and direction. This procedure can be performed every time the visitor experiences a position error. At least one camera is required to initialize the PDRS with the starting position and calibrate the navigation parameters.

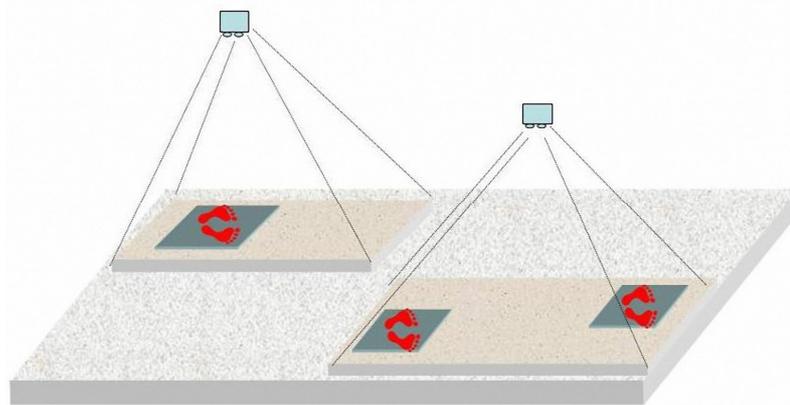


Figure 36: Recalibration area – tiles

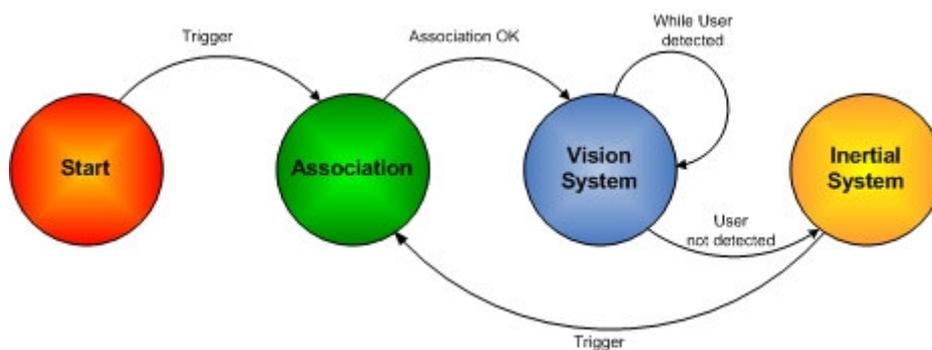


Figure 37: VTS-PDRS finite state machine

The FSM reported in Figure 37 describes the main states of this approach. The “Start” state refers to the initial instant in which the user takes for the first time the mobile device. The request of a recalibration causes the transition from the “Start” to the “Association” state, in which the association algorithm is computed. If the algorithm succeeds in associating the ID to

the device, the position coordinates are sent to the mobile device and the FSM reaches the “Vision System” state. In this state the position is provided by the VTS, and the real-time calibration of the PDRS is performed. When the VTS does not anymore detect the device, the system joins the “Inertial System” state, initializing the starting position and direction and with calibrated parameters.

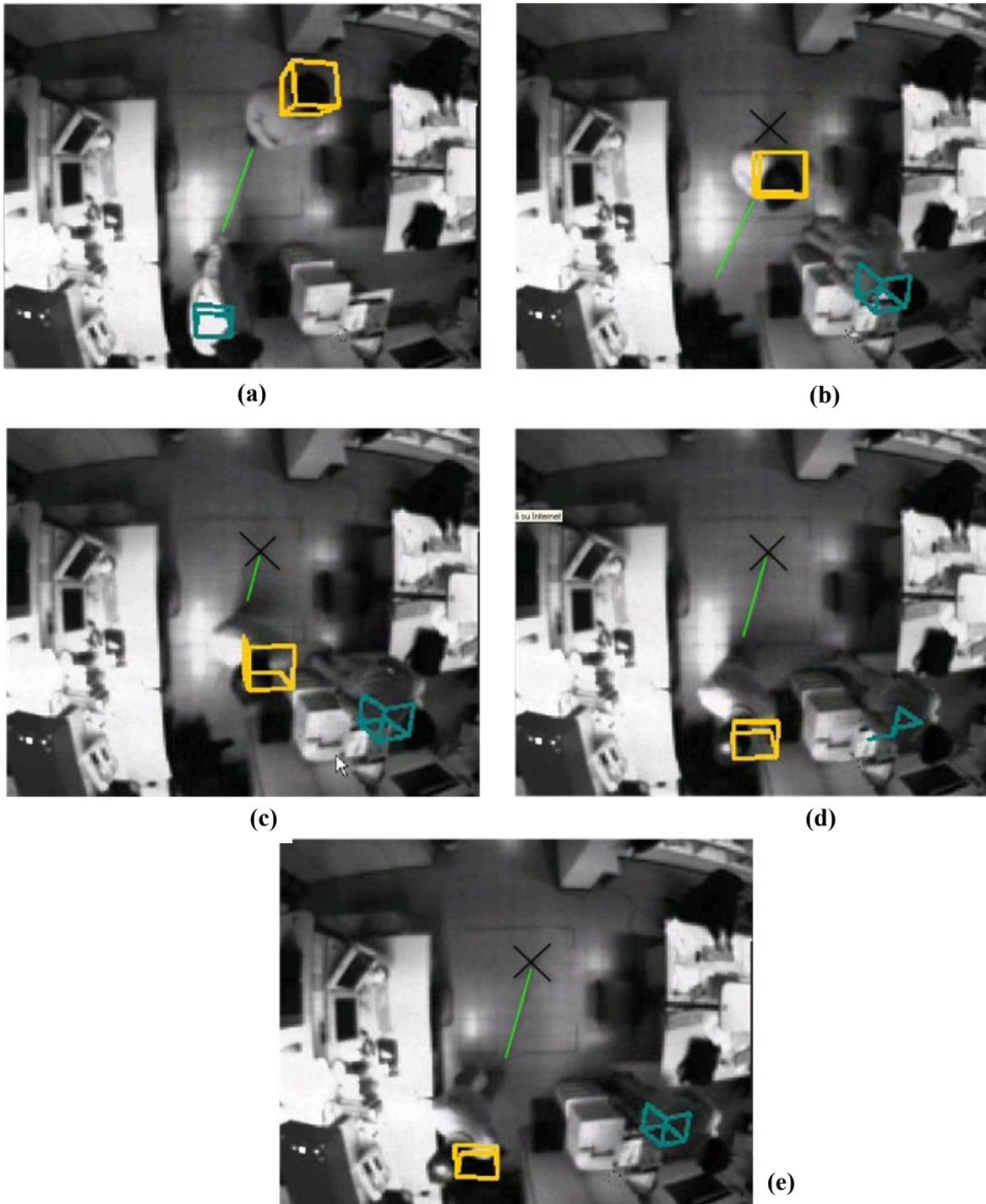


Figure 38: System calibration with two users

The system assumes that the camera used for the initial calibration is known. If others cameras are installed, the estimated PDRS position of the user is considered, in order to

understand roughly which camera the user is under. This assumption is based on the fact that cameras are far enough from each other. So even if the PDRS has drift problems, the estimated position could be in any case used to estimate the closer camera.

Figure 38 shows two different users under the area covered by the camera: the first one (yellow box) has the mobile device with him, while the second one (blue box) is without. The user detected with the yellow box requires the recalibration service (Figure 38 (a)). He starts to move only when the system associates the right detected person. Every time the system associates a PDRS device with a VTS trajectory, it store the resulting VTS positions in a file called "Traiettoria.txt".

3.2.5 System Architecture

The system architecture is base on a client-server architecture in which two servers are involved (Figure 39). The first one is the Vision server, developed by Computer Vision Lab in the University of Bologna, that receives messages sent by the stereo camera connected through the FireWire cable. The Stereo Vision Tracking Algorithm estimates the user position using the technique described in section 3.2.1.1 and communicates the VTS position to the Localization MML Server, that performs the calibration and positioning algorithm. The Localization MML Server is also charged to run the identification algorithm (section 3.2.3) using both information provided by the Vision server and the mobile devices. The Localization MML Server sends the corrected position and direction to mobile devices that requested the calibration. All the communications between client -server, and between the two servers are wireless.

The mobile device could be the Whyre, or any other portable device equipped with a MSU and a wireless interface. Every VTS system deployed in the museum acts as an on-demand *Realignment Server* (RS) [Cutillo'06].

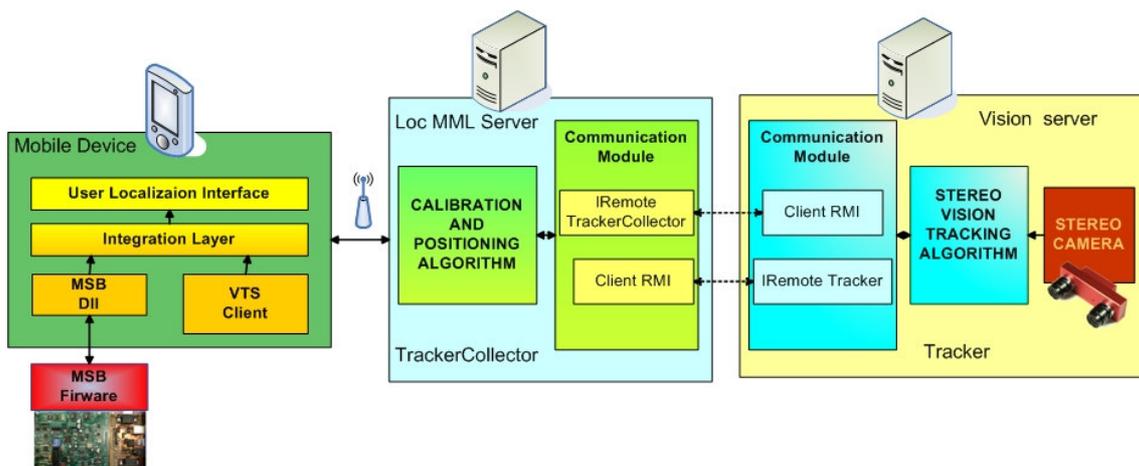


Figure 39: VTS-PDRS system architecture

3.2.6 Conclusions

The prototype implementation shows that it is possible to use VTS to improve the reliability and the accuracy of PDRS, without affecting the intrusiveness of the overall system, but enhancing potential services provided by the museum or other types of environments, like security and people counting.

The system require at least one camera to perform the initialization and calibration when the user takes the device for the first time. Real time calibrations are supported. At the moment a semi automatic approach to calibrate the MSU in multi user situations has been implemented and tested. Problems related to the fully automatic implementation of the system exist, especially when more than one user is moving, but the concept of its feasibility has been demonstrated.

The different calibrations procedures implemented during this research have been described, highlighting the gained benefits for the PDRS.

The use of a compass together with a more reliable algorithm to detect the pedestrian tracking can allow an improvement of the integrated system. On the other side, VTS could be improved by using visible markers that facilitate the switching between the two systems.

3.3 Dead reckoning supports GPS in pedestrian navigation

A continuous tracking system needs to locate mobile users both indoor and outdoor. This section presents the problems related to outdoor localization in CH sites. The proposed solution takes advantages from the combination of the wearable inertial sensing platform with the GPS measurements.

GPS is undoubtedly the most used outdoor localization system; however, a system based on GPS technology will be applicable only in open environments and some shaded areas, but with significant degradation in the latter case. A pedestrian typically moves in dense urban areas (along sidewalks), inside buildings, in tunnels, and under foliage, where GPS signals often fail to reach the user. To overcome the limitations of GPS, the pedestrian dead reckoning system is typically used in conjunction. Even if GPS and DR systems are prone to errors, their dynamics are not correlated and hence their combination allows to overcome the inherent weakness considered in a standalone functioning way.

Many developed algorithms simply switch between pure GPS and pure DR, while others use sophisticated filters to integrate the two different techniques, sometimes resulting in a heavy computation requirements not possible on mobile device.

Our approach is based on a smart switching system, that uses accurate GPS data to continuously calibrate inertial information. When GPS position is available and its accuracy is “acceptable”, tracks the user and perform the DR calibration, by correcting the gyroscope and updating step length parameter. When GPS information is unavailable or inaccurate, traveled distance is calculated by using the MSU algorithm discussed in section 3.1.

Some measurement tests performed with GPS receiver will be provided.

3.3.1 GPS Pedestrian Navigation

The combination of GPS with PDRS is not a novel approach, but it has been extensively studied by several researchers over the years, in various domains and it involves a wide range of techniques [Ladetto'00; Jiravimut et al.'03; Renaudin et al.'07].

In this work GPS measurements are used to initialize the absolute starting position and direction of the MSU, calibrate step length parameter, and periodically correct gyroscope drift error.

Experiments show an inferior behaviour of the MSU in outdoor environments, mainly due to the different types of surface. An explicit example is shown in Figure 40 (that is the total trajectory of Figure 18).



Figure 40: GPS vs. PDRS In Pompei

This experiment has been conducted in the Archeological Site of Pompei, where there is a cobblestone ground. Under this condition the gyroscope produces a relative high error in the

dead reckoning trajectory. The use of GPS to correct inertial parameters can highly improve the accuracy of the localizations, and moreover, can be used to initialize the MSU starting point.

Advantages in the use of GPS, especially in archeological sites relies on the total absence of infrastructure. It is not possible to install a support infrastructure, due to the quasi total absence of power sources and external control.

On the contrary, even if this image is tending to mislead, it is not possible to use only the GPS, because, like in Pompei, there are some indoor areas in which the GPS does not work properly.

3.3.1.1 GPS Receivers and Protocols

Two different GPS receivers have been tested and used in our experiments. The first one is a GPS receiver built in our laboratory, that mounts the RGM-3000 series [Royaltek] consisting of SiRF star II chipsets technology. The receiver has been connected to a notebook through an USB interface. The second and more recent one is the GPS receiver produced by Holux [Holux] mounting a SiRF star III chipsets technology, connected through a Bluetooth wireless connection.

In general, GPS receivers use a variety of languages/protocols, such as NMEA, Sirf, Garmin, Delorme, etc... While all GPS receivers output the NMEA, only receivers using the Sirf chipset can output Sirf [SiRF].

In our applications we use the Sirf binary protocol instead of the standard NMEA text protocol, because it allows a major control in setting and retrieving data. The Sirf Binary Protocol is organized in different messages that contain all the receiver measurements in the format shown in Figure 41. A detailed review on Sirf protocol is reported in [SiRF].

Start Sequence	Payload Length	Payload	Message Checksum	End Sequence
0xA0 ¹ , 0xA2	Two-bytes (15-bits)	Up to $2^{10} - 1$ (≤ 1023)	Two-bytes (15-bits)	0xB0, 0xB3

Figure 41: Sirf message

3.3.1.1.1 Evaluation of GPS receivers

The initialization of the GPS receiver with correct parameters is important to increase the precision and accuracy of the retrieved position information.

The first consideration concerns the *static navigation*, that allows to prevent multipath errors and increase sensitivity to weak GPS signals. This function optimizes the configuration for “on-road” solutions, but it also creates a rather big problem for “off-road” applications like

GPS used by pedestrians. Therefore, in order to develop a pedestrian tracking system it is very important to switch off this option. The second consideration concerns the Satellite Based Augmented System (SBAS). In order to have a better performance the SBAS has to be switched on. The third consideration is related with the GPS smoothing function that smoothes estimated position based on acceptable variances from the last calculated position. This assists in eliminating any sporadic position jumps possibly caused by multipath, for example.

Last but not the least the baud rate set in the receiver needs to take in account the amount of SIRF information required by the user. A low baud rate could produce a visible delay in the provided GPS position.

Some experiments have been conducted to evaluate the quality of the two GPS receivers. The test involves the time to first fix of the GPS, depending on the starting condition:

- **Cold start:** A cold start happens after a receiver has not been used for an extended period, or when the receiver is activated at a large distance from the place where the stored almanac was retrieved. It deletes both the almanac and the ephemeris and downloads new data from the GPS constellation. A cold start can take up to 50 seconds.
- **Warm start:** Warm start uses the stored almanac, deletes ephemeris data and downloads new ephemeris data from the GPS constellation. A warm start happens after a certain period of 'no coverage'.
- **Hot start:** A hot start may happen after a short loss of coverage and is usually shorter than 10 s.

	Experimental	From datasheet
Hot start (almanac + ephemeris)	10 seconds	<8 second
Warm start (almanac + ephemeris)	39 seconds	<38 seconds
Warm start (almanac)	36 seconds	<38 seconds
Cold start (without reset)	45 seconds	<45 seconds

Table 7: Royaltek Performances

	Experimental	From datasheet
Hot start (almanac + ephemeris)	1 seconds	<1 second
Warm start (almanac + ephemeris)	39 seconds	<38 seconds
Warm start (almanac)	37 seconds	<38 seconds
Cold start (without reset)	56 seconds	<42 seconds

Table 8: Holux Performances

Experiments, as expected, show that the SiRFIII chipset, thanks to the high sensitivity, has a better accuracy, that is reflected in a faster Time To First Fix (TTFF). Experiments report that delay of Holux in hot start condition is equal to the GPS frequency update.

Figure 42, Figure 43 and Figure 43 report the experiment of the GPS availability in urban canyon. As shown in the higher sensibility of Holux receiver results also in the capability to locate mobile users in hostile environments.

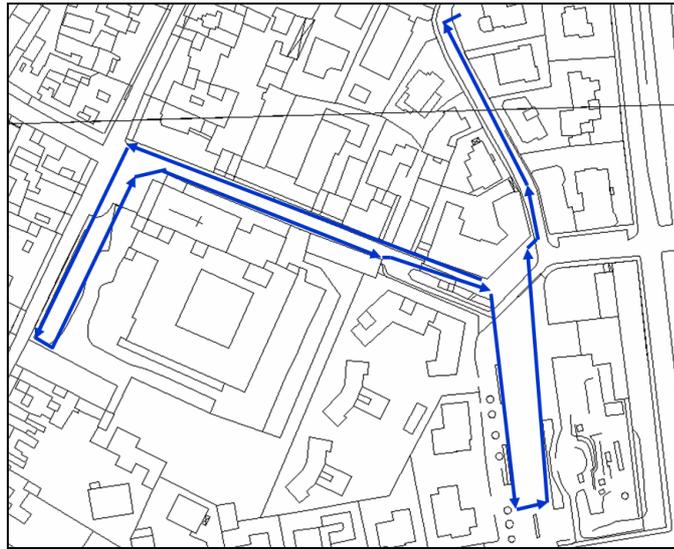


Figure 42: Real trajectory

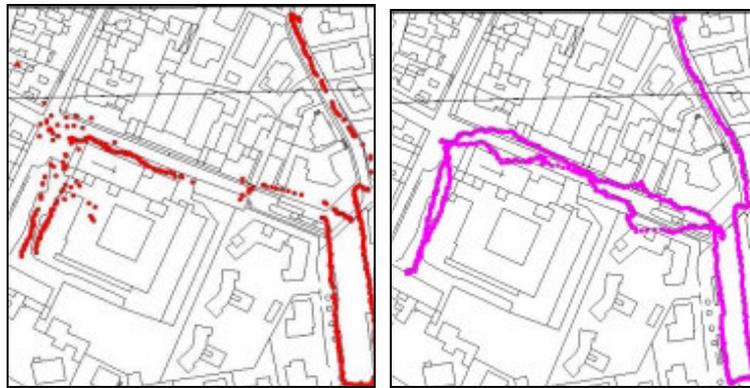


Figure 43: Royalttek trajectory

Figure 44: Holux trajectory

3.3.1.1.2 Validity and accuracy of GPS fix

GPS is affected by errors caused by different sources. The accuracy of the system (and of the measurements) is determined by the sum of all these errors. The accuracy of position, heading and velocity determined by the GPS can be expressed as the product of a geometry factor and a pseudorange error factor as follow:

$$(\text{error in GPS solution}) = (\text{geometry factor}) * (\text{pseudorange error factor}) \text{ [Kaplan].}$$

Error sources of the *pseudorange error factor* can be assumed to be satellite clock errors, ephemeris prediction error, relativistic effect, ionospheric effect, tropospheric delay receiver noise and resolution, multipath and shadowing effects [Kaplan].

The *geometry factor* expresses the composite effect of the relative satellite/user geometry on the GPS solution error. It is generally called “dilution of precision” (DOP) and it is associated with the satellite/user geometry. DOP describes the validity of the current constellation for positioning. We can define different types of DOP, according to parameters that are used to estimate the DOP. The widely used is the HDOP (Horizontal DOP).

Smaller DOP corresponds to high degree of accuracy of the GPS (table 9).

DOP	Classification	Description
1	Ideal	This value corresponds to the highest level, ensuring the most exact localization.
2-3	Excellent	With this level of DOP, the position accuracy is considered accurate for the most of applications.
4-6	Good	This level is the lowest acceptable level to the professional applications.
7-8	Moderate	Computed positions are usable, but the accuracy has to be improved. Need to go in open sky environment.
9-20	Limit	This level provide a low position accuracy. The obtained information can be used only to provide a coarse location data.
21-50	Weak	Measurements are inaccurate and cannot be exploited.

Table 9: DOP classification

The monitoring and control of DOP is one of the keys to reduce the problem of inaccurate measurements provided by GPS.

The developed algorithm evaluates the goodness of the GPS measurement by considering the DOP value and two different output messages of the SIRF protocol:

- 1) The field MODE2, included in the Message ID 2, has to be 2 or 18. It means that almost 5 satellites are used in the position computation;
- 2) The field MODE 1, included in the Message ID 2, has to be 4 or 19 , or 132 or 147 (if there is the SBAS signal). It means that the position computed by the GPS has been estimated by signal satellites and not by the internal algorithm of the receiver.
- 3) The new computed position has to be “near” the old value. With this control we should avoid situations in which there is the jump of the GPS data in an inexact position. This control is made considering the following criteria:

$$\text{Time} < 1\text{s} \text{ dist}_{\text{max}} = 2,5 \text{ meters}$$

$$\text{Time} < 2\text{s} \text{ dist}_{\text{max}} = 5 \text{ meters}$$

$$\text{Time} < 10\text{s} \text{ dist}_{\text{max}} = 1, 2 \cdot \text{Time}$$

Another problem related to GPS receiver is the random behaviour that appears when the receivers speed is not enough to calculate the heading. Hence the position, instead to be fixed, jumps around the true location, obtaining a cloud of points. This error in part is corrected activating the SBAS (EGNOSS).

In order to be sure to avoid the “jumping effect” the algorithm evaluates the GPS speed and filtrates all the positions computed by the receiver when the velocity is lower than an estimated threshold.

Experiments performed with RGM 3000 show that when the user is no walking the GPS speed on the three axis has an absolute value lower than 0,25, as shown also in Table 10. Therefore the developed algorithm includes this control.

	X Speed (m/s)	Y Speed (m/s)	Z Speed (m/s)
Stop point 1	0,125	- 0,125	0,125
Stop point 2	0,25	-0,25	0
Stop point 3	-0,125	0,125	0,25

Table 10: Value of GPS speed when the user is stading.

3.3.2 Pedestrian Dead Reckoning Calibration

The continuous outdoor tracking system proposed in this section is a switching system in which the user position is provided by a GPS receiver, when available with high accuracy, and by the PDRS when GSP is not available. Combining the two system the following correction are performed:

- Initialization of the MSU position;
- Calibration of the parameter α used to estimate the step length;
- Initialization and correction of the heading.

3.3.2.1 Position Initialization

Position initialization is a crucial point in the combination of DR and absolute systems. The starting position of the MSU is computed considering the last accurate position estimated by the GPS using criteria reported in section 3.3.1.1.2. Then the use of GPS and PDRS is alternated depending on the accuracy of GPS. The GPS data are used as long as it reports a high accuracy. If this condition is not met, then the system automatically switches to PDR mode.

Figure 45 shows that the switching mechanism needs to be assisted by a heading correction algorithm, in order to calibrate the MSU estimated direction. The spurious position in

the detected trajectory has been caused by an anomalous switch from PDRS to GPS of the algorithm and need to be filtered.

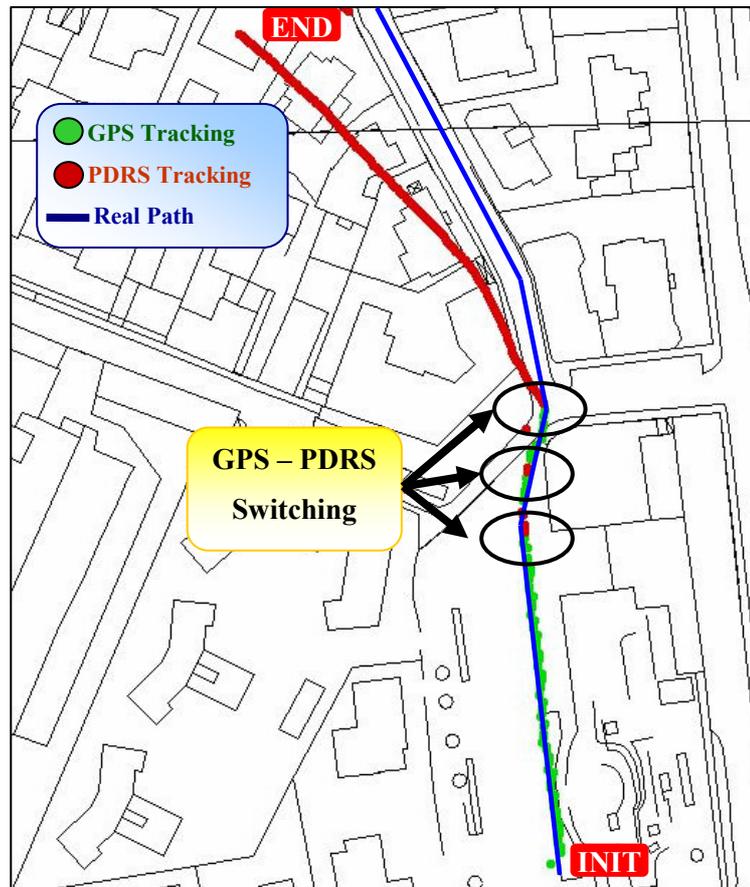


Figure 45: Combination of PDRS with GPS

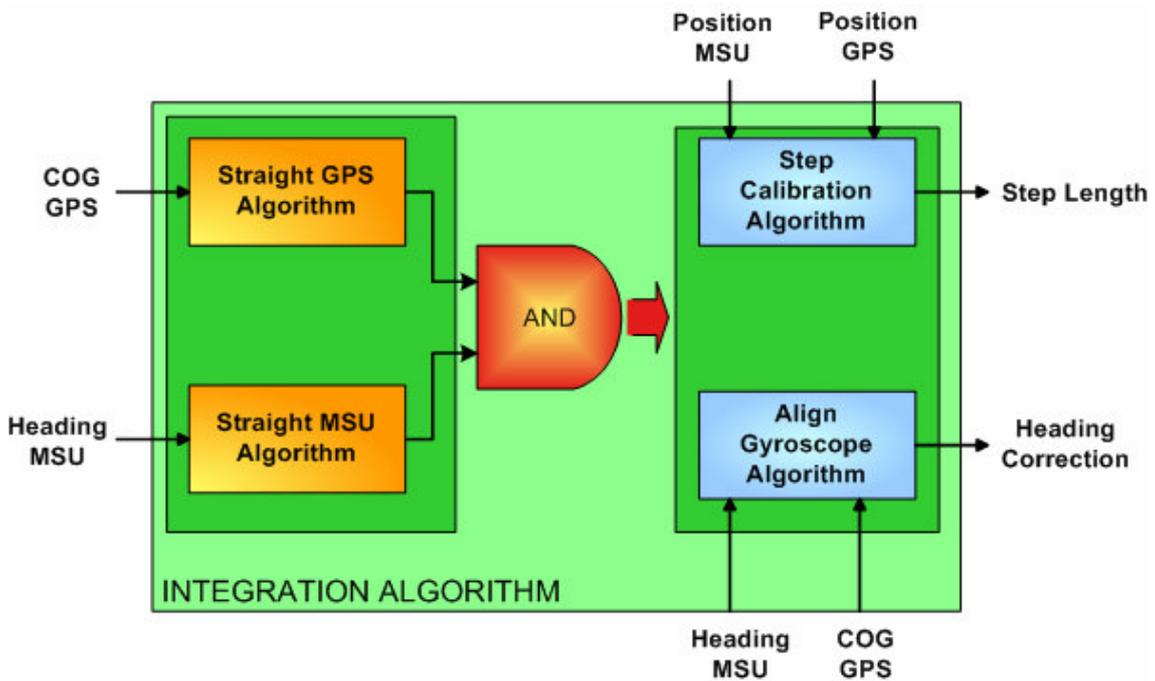


Figure 46: PDR alignment

3.3.2.2 Heading Initialization and Correction

Gyroscope needs to know the initial direction in order to compute the instantaneous heading. The initialization is performed using the Course Over Ground (COG) estimated with good GPS signals. After providing the absolute initial heading, it is also required to periodically realign the gyroscope heading to cancel drift and saturation problems.

The COG detected by the GPS when accuracy conditions are satisfied is constantly filtered. In this way, gyroscope heading is constantly compared with GPS azimuth and eventually resynchronized if an error occurs.

The algorithm illustrated in Figure 46 shows that, in order to perform the calibration process, GPS and MSU have to detect a straight walk trajectory. If these two conditions are satisfied and the GPS position is accurate (according to the proposed criteria), gyroscope alignment and step calibration are computed.

“Straight GPS Algorithm” checks if the three most recent COG measurements satisfy the following condition:

$$MeanCOG - \varepsilon \leq newCOG \leq MeanCOG + \varepsilon$$

where *Mean_COG* is the mean value of the direction estimated during a straight walk and ε is an estimated threshold computed as follow:

- < 6 satellites $\rightarrow \varepsilon = 4,5^\circ$
- = 6 satellites $\rightarrow \varepsilon = 4^\circ$
- > 6 satellites $\rightarrow \varepsilon = 3^\circ$

Simultaneously the “Straight MSU Algorithm”, based on the same approach, checks the straight walking condition using gyroscope measurements.

Because of the sampling rate of the two systems are different (GPS at 1 Hz, MSU at 8 HZ), the algorithm computes every second the mean value of all the gyroscope headings detected during one second. When the algorithm detects that the user is going straight, the GPS COG and the mean value of the gyroscope heading are compared to established if the MSU needs to be calibrated. The correction is applied only if the difference is bigger than a prefixed threshold, that depend on the number of visible satellites.

- < 6 satellites \rightarrow threshold = 5°
- = 6 satellites \rightarrow threshold = 4°
- > 6 satellites \rightarrow threshold = 2°

The heading correction computed using the proposed algorithm is shown in Figure 47.

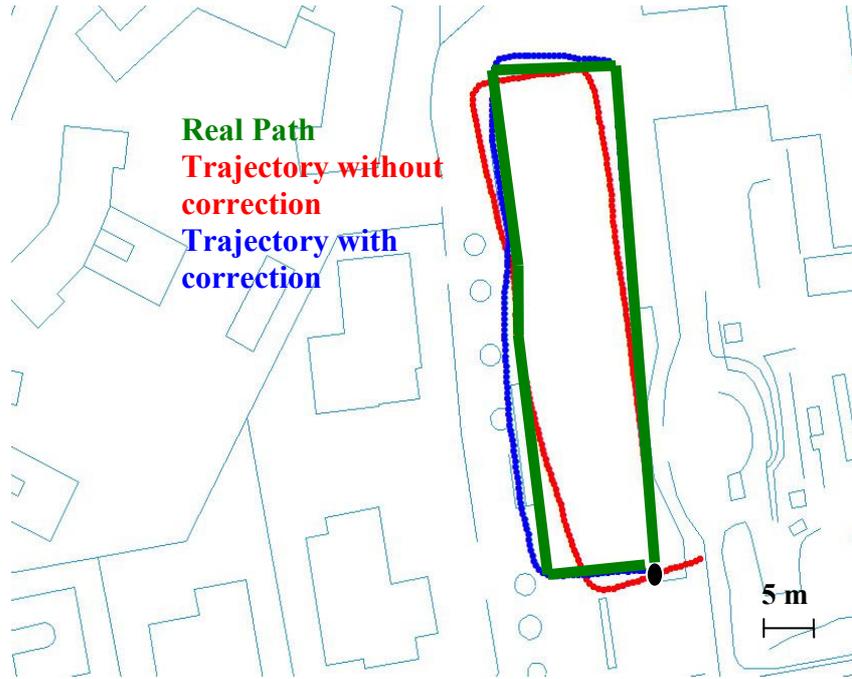


Figure 47: Heading correction

3.3.2.3 Step Length Calibration

The PDRS requires a user specific calibration of the parameter α to compute the stride length. When GPS is available, individual models for the step length are calibrated. The algorithm performs the computation only if the “straight walk” condition is verified (section 3.3.2.2). Step length calibration algorithm adjusts the default parameter α by comparing the mean value of the step length estimated by GPS with the mean value of the step length detected by the PDRS. In order to estimate the gait cycle length the algorithm computes:

$$\text{step Length GPS} = \frac{\text{distance_GPS}}{\text{number of steps}}$$

The computation of StepLengthGPS requires the estimation of the Distance_GPS, that is computed through interpolation, considering two successive GPS measurements and the instant times of PDRS step detection. In particular the interpolation is performed to determine the initial and the final part of the GPS trajectory.

Considering Figure 48, the initial part of GPS trajectory is estimated through interpolation using the GPS positions in t_0 and t_1 and the instant time in which the PDRS detects step 1. The final part of GPS trajectory is estimated through interpolation using the GPS positions in t_5 and t_6 and the instant time in which the PDRS detects step 8. Then Distance_GPS is estimated by summing the Euclidean distance between two consecutive GPS positions if $\text{Start_Time_PDRS} < \text{timeGPS} < \text{End_Time_PDRS}$, and the interpolated initial and final distances. Once the

Distance_GPS has been estimated, to obtain the stepLengthGPS, Distance_GPS is divided by the number of steps detected by PDRS.

The new parameter α is updated only if at least five straight steps are performed:

$$\alpha_{NEW} = \alpha_{PREVIOUS} \cdot \frac{L_{GPS}}{\frac{1}{n} \sum_{i=1}^n L_{PDRSi}}$$

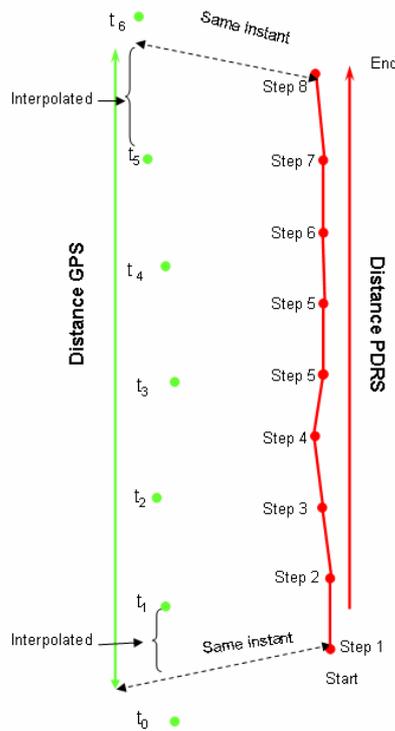


Figure 48: Step Length calibration

User	Real Distance	Estimated distance without calibration (k=0,927)	Error	Estimated distance with calibration	Error
Alessandro	100 m	103,74 m	+3,74 %	110,3 m	+10,3 %
Daniele	100 m	132,35 m	+32,35%	108,5	+8,5 %
Marina	100 m	123,99 m	+23,99 %	105,17 m	+5,17 %

Table 11: Estimated distance with calibration

Table 11 reports the preliminary result using the proposed GPS approach. The error of the distance estimated with the calibration is smaller than the estimated distance without calibration, even if, as expected, it is less accurate than the VTS calibration process.

The calibration process is not constant and can vary according to the goodness of the GPS signals.

3.3.2.4 Evaluation and Results

The presented combined system has been tested in place Carducci in Bologna. Experiments show that the alternation between the GPS and PDRS is quite accurate: when the GPS signals are not good the system switches automatically to PDRS (Figure 49).

However, the overall detected trajectory presents some spurious points, especially when the PDRS mode is activated, due to instantaneous switching from PDRS to GPS. As already explained this anomalous behaviour requires further analysis.

The “jumping effects” caused by the standing state of the user are filtered by the algorithm. Further analysis should be conducted to make the switch from GPS to PDRS smoother.

Figure 49 shows that the step length calibration and gyroscope heading alignment with the GPS provides acceptable results, resulting in an exact estimation of the total length of the trajectory.

This section shows first results of the integration between PDRS with GPS. Further improvements are required to increase the accuracy and reliability of the overall algorithm. Kalman filter or Particle filters will be considered, attempting to maintain low computational load and complexity of the problem.

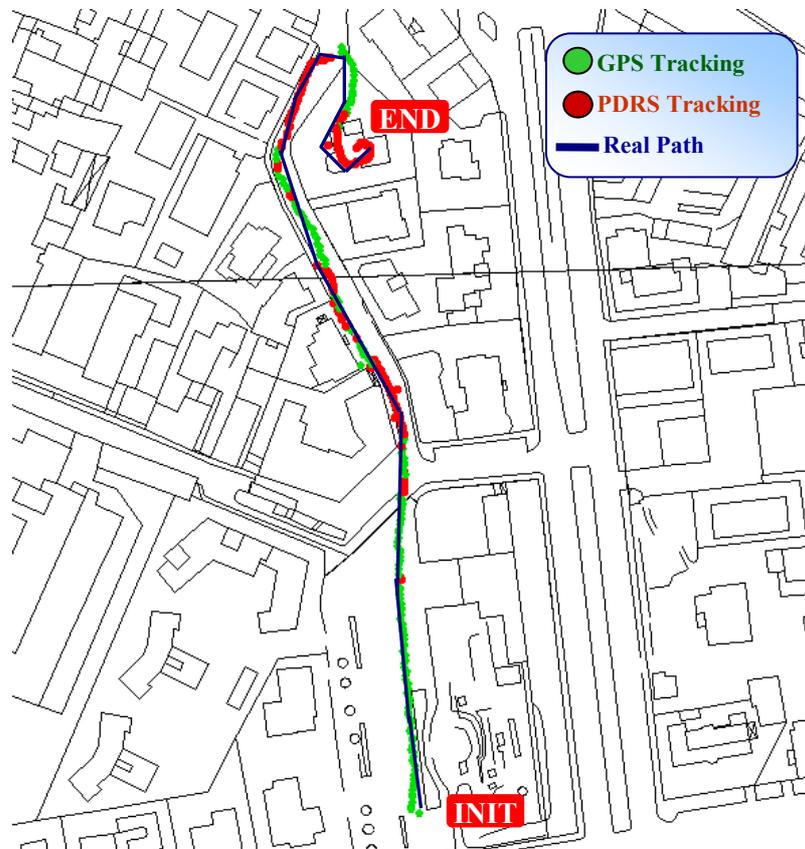


Figure 49: Combination of GPS with PDRS

3.3.3 Conclusions

The combination of GPS and PDRS improves the reliability and precision of the overall estimated trajectory. The integration with the GPS provides starting position, initial direction and step length calibration to the MSU.

The proposed combined approach is a simple and efficacy method, that does not require high computation and can run on every portable device, also with low power processor. It provides a simple and low cost filter that eliminates part of the residual noise in GPS position, relying only on basic mathematics, and is able to calibrate the MSU with the right parameters.

Calibration using GPS, is evidently dependent on the accuracy of the GPS, that can vary according to the type of environment. For example clouds or urban canyon could highly disturb the algorithm in performing calibration, sometimes resulting in erroneous parameters.

3.4 An indoor identification and tracking system: RF and vision integration

This last section refers to the pedestrian identification and localization system developed at INRIA-Grenoble. It relies on the integration of radio frequency and vision technology. It is not trivial to identify people using a vision based tracking systems that monitor wide areas, and that are not focalized on the face recognition. The proposed algorithm attempts to identify and track users carrying a mobile devices thanks to the combination of the strong identification of RF-based location sensing with the accuracy of computer vision-based-tracking. The proposed system provides a novel approach for multi-scale and multi-target indoor location sensing.

3.4.1 System Overview and main system components

The proposed approach aims to combine the strong identification provided by the WLAN tracking system with the high precision typical of the VTS, in order to obtain a continuous tracking system able to uniquely identify and track users. This solution could be addressed to “Smart Conference”, or in situation where all the participants need to be physically located, and services based on the actual user’s context are provided. In this scenario it can be imaged that every participant carries a device with him (notebook, PDA, tablet pc) with a wireless connection (Figure 50).

The proposed positioning and identification system provides two different granularities: a better localization inside rooms equipped with cameras, and a coarse one when users go out and WiFi localization is activated.

The developed system has been integrated in a middleware for pervasive environment called O3miscid [Emonet et al.'06].

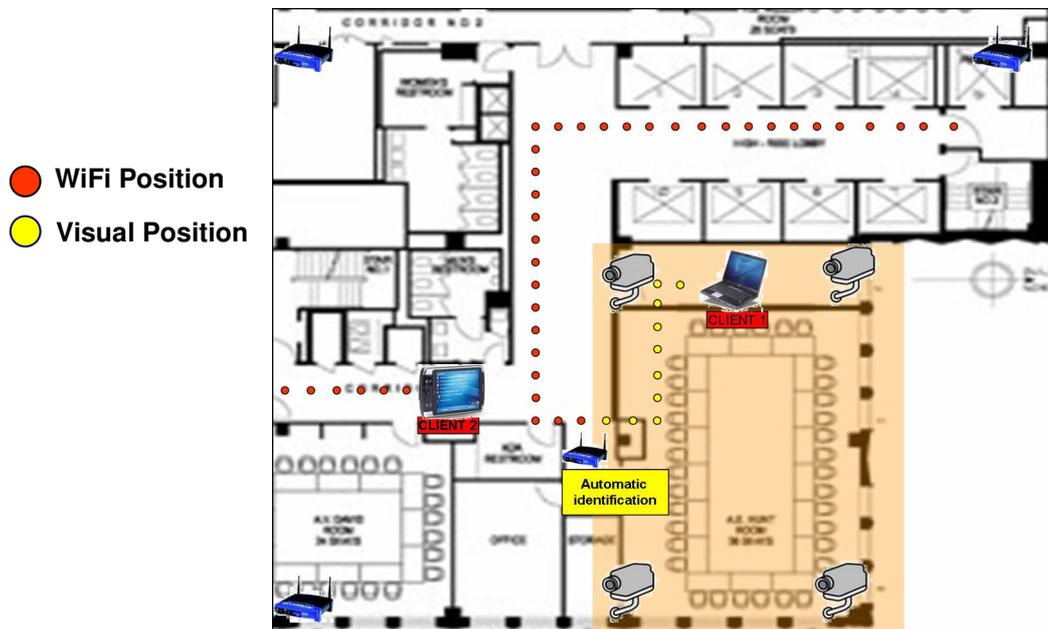


Figure 50: Identification-positioning system example

3.4.1.1 WLAN-Based Tracking and Magicmap

RF based approaches - more specifically, the wireless local-area network (WLAN - IEEE 802.11) radio-signal-based positioning system - have drawn great attention in recent years.

A WLAN-based tracking system (WTS) has distinct advantages over all other systems (see 2.4.4.1). However it shows a relevant drawback related to its low measure precision due to the multipath effect of the signal strength. Generally, the signal propagation in an indoor environment is subject to the reflections, diffraction, and scattering of the radio waves caused by the structures within the building. The transmitted signal reaches the receiver via multiple paths, causing fluctuations in the received signal envelope and phase. Moreover, complex environments cause severe multipath effects, dead spots, noise, and interference.

Considering that the objective of the assigned project does not focus on the deployment of a new 802.11 localization system, an existing application has been chosen. In particular Magicmap system [Ibach et al.'05] has been selected over all other systems (i.e. PlaceLab, Ekahau;..) because it satisfied the needs to have:

- an open-source application;
- a client-server application.

MagicMap (Figure 51) is an application developed by the University of Berlin. It uses a propagation model to locate mobile devices. Clients exchange information on AP and reference

measurements. In particular every node senses its environment and uses the observed data to calculate its location. From that, location specific actions can be triggered. Calculations can be done redundantly on multiple nodes to improve fault tolerance, in particular, to prevent a minority of malicious nodes to affect system stability.

In the current implementation MagicMap uses WLAN equipped Laptops, PDAs, and Smartphones that exploit WLAN signal strength to sense the environment and calculate their positions. Two different kind of information could be used in order to compute the position:

- Signal strengths of surrounding APs
- Reference Points (RP): a RP is a “finger-mark” measured by the client during a calibration phase. A RP contains signal strength information observed by client in a specific location.

The SpringLayout algorithm framework of the Java Universal Network/Graph [JUNG'06] is used to estimate the client position. Edge lengths between clients and APs are determined by MagicMap evaluating the RSSI of the received signals. The SpringLayout algorithm moves the nodes trying to optimize the distance such as lengths of edges best match calculated physical distances. It automatically rearranges nodes and edges of a graph based trying to minimize the deviation of edge lengths. Reference measurements are considered in an averaged k-nearest-neighbors algorithm. If the algorithm is iterated a few times, the graph reaches a stable position. Thus, the graph converges into a “magic map”, where nodes are located approximately at their true physical position.

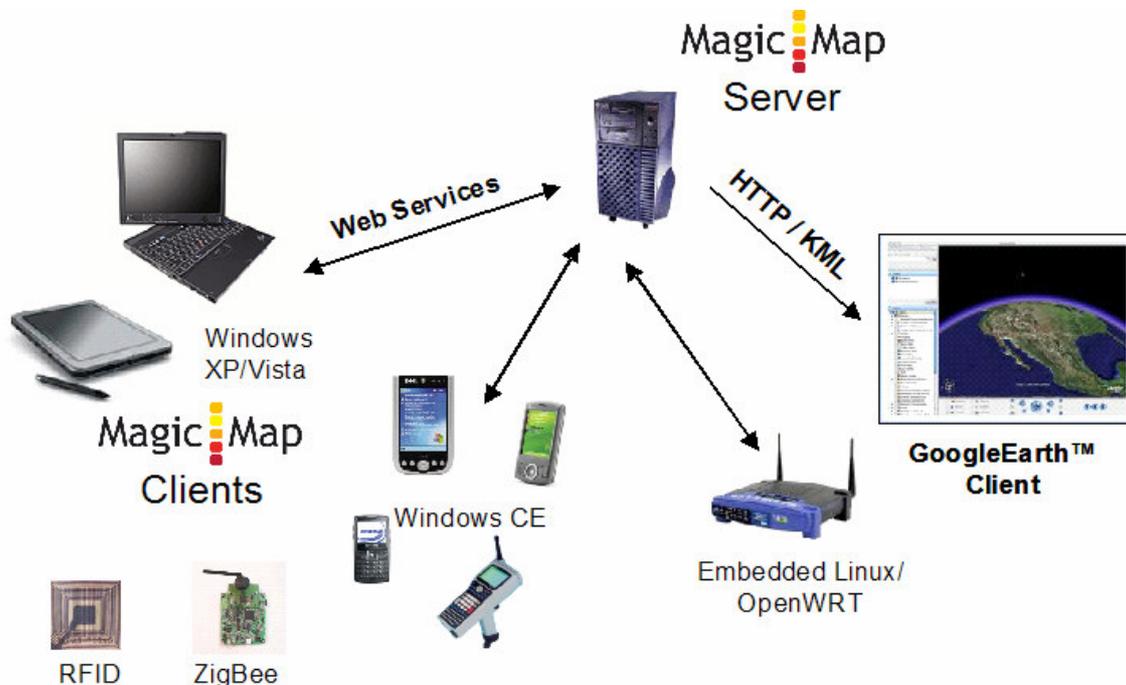


Figure 51: MagicMap Overview (from Magicmap site)

3.4.1.2 Vision Tracking System

The VTS used in this application is the 3D video tracking system developed by the Inrialpes-Prima research group [Ferrer-Biosca et al.'07]. It is able to detect and track mobile entities in real-time using multiple cameras. 3DTracker uses an approach based on the probabilistic paradigm of Bayesian reasoning: in order to track 3D coordinates of people, a position estimation is obtained tracking results from several 2D trackers [Caporossi et al.'04] running on the video images of each camera, computed using a sensor model, with a priori knowledge of a person's motion - the motion model. Each couple camera-detector is running on a dedicated processor. All inter-process communication is managed with O3miscid, the object oriented middleware for service connection.

The output of the 3D tracker are the position (x, y, z) of each detected target as well as the corresponding covariance matrix (3x3 matrix describing the form of the bounding ellipsoid of the target). The generated 3D target positions correspond to real positions in the environment. The 3D video tracking system provides high tracking stability. The detection is done in a certain zone of the scene named *detectionRegion*. The detection region is typically placed near the door, or in places where people usually enter the scene.

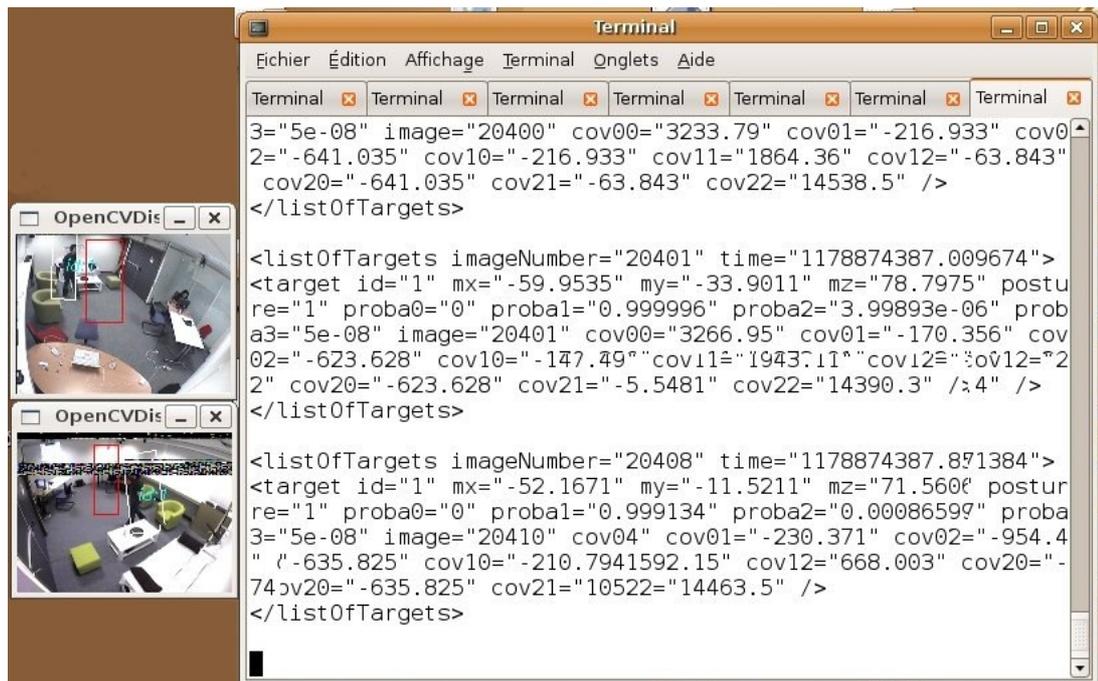


Figure 52: 3D Tracker Interface

3.4.2 System Integration

The proposed solution is based on the combination of Magicmap with the more precise 3DTracker. Minimum system requirements are:

- identify and localize with high accuracy all users that are in rooms equipped with cameras;
- for other people that are not inside this room supply a more rough position information.

The mixed system works switching between the WTS and the 3D tracker, according to the area the user is walking through. Considering that the 3D tracker cover an entire room, when the user is inside the room the position is supplied only by the 3D tracker, because of its high resolution. Once the 3D tracker does not anymore detect the device, the position is provided by the WTS.

The two major issues of the proposed approach are:

- Detect when a user with its mobile device is entering in the supervised room;
- Associate the Mac Address of this user with the identification ID of the new target detected by the VTS.

In this way it is possible to uniquely track moving “devices” provided with a WiFi card carried by a person. Starting from this hypothesis, when the user enters in a supervised room, the system automatically associates the ID of the target detected by the camera with the Mac Address of the device, allowing the identification of the user. Once the identification has been done the user positioning information is provided by the VTS. At this point the user can move freely inside the conference room without portable device, as the VTS can easily track him.

It is important to point out that when the user exits from the conference room he has to pick up the device in order to have a continuous localization.

3.4.2.1 Automatic detection of the entrance in the supervised room

Experimental tests conducted inside INRIA show that the mean error of Magicmap in estimated position is about 6 meters. This error is also due to the physical position of APs. Reuse of already installed infrastructure help in avoiding intrusiveness, but sometimes does not achieve the required precision. As explained in section 2.3.3.3 APs are usually placed in way that is not the best configuration for localization purposes.

To overcome this problem we tried to model the user behaviour when he approaches and enters into the smart room.

Experiments have been conducted in the Smart Office at INRIA Rhône-Alpes, a large office equipped with the 3DTracker system. Figure 53 shows the state through which we can model the user that enters in such a room. The initial state is “Outdoor meeting room”. The graph shows that if the user enters the meeting room, he has to pass through the “Under the door” state. If both systems are able to detect when the user is in “Under the door” state we could automatically associate the id provided by Magicmap with the target detect by 3Dtracker.

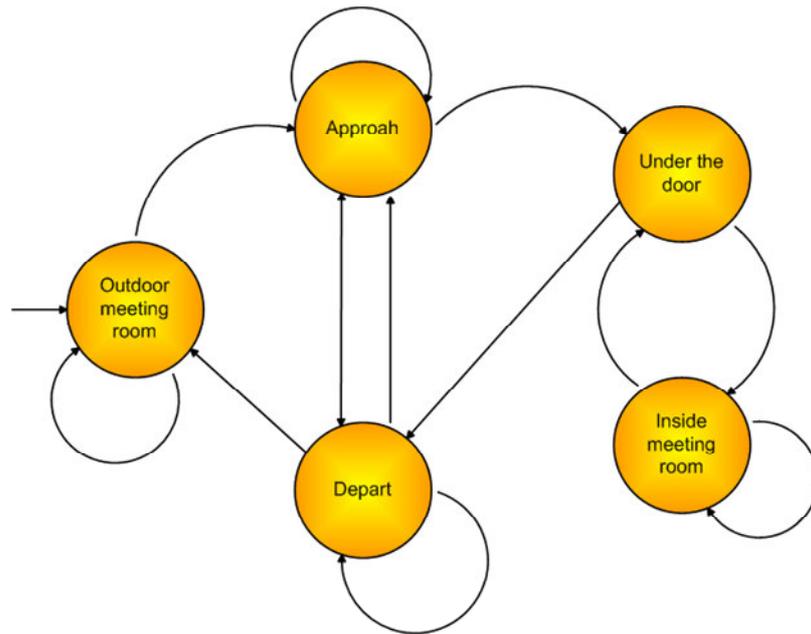


Figure 53: User states

From a 3DTracker point of view it is quite simple to detect this instant; it is sufficient to place the detection region (Figure 54) close to the door.



Figure 54: Detection region.

From the Magicmap perspective the detection of the state “under the door” is not trivial: the problem is related to the relevant error computed by Magicmap in estimating the position. Experiments conducted in INRIA show that MagicMap is not able to detect with an acceptable accuracy when the user is entering in the room. The mean value error is 6 meters. For this reason, the adopted solution consists in installing an AP over the entrance door of the conference room. We conjectured that it might be possible to detect when a user is moving toward this AP and when he is under the AP based on WiFi signal strength features. Such a conjecture was supported by our qualitative observation: the RSSI of the installed AP appears to have a different trend if the user is approaching, is departing from, is outside or is inside the meeting room (Figure 55).

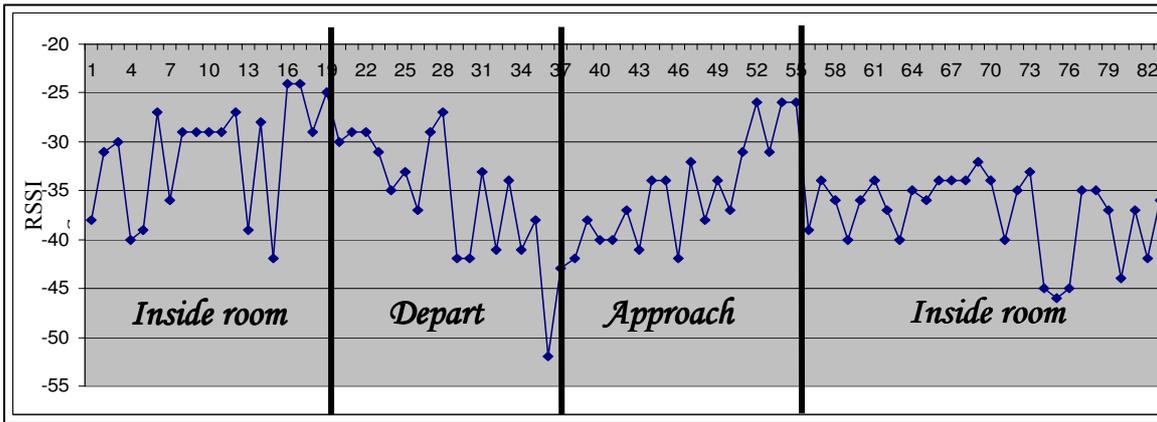


Figure 55: Rssi of the nearest AP in the different state of the client.

We capture the different trends detected when the user is inside, he is departing from or he is approaching to the meeting room by computing a temporally windowed, running linear regression of the received signal strength of the strongest AP at any given time. That is, at any given time, we first find the AP with the strongest signal and then compute the linear regression of that AP’s signal over a short interval ending at the given time. The linear regressions were computed with a 10-seconds window.

Figure 56 shows values of the computed linear regressions. Considering the “depart” phase, reported values are smaller than 0 (excluding 2 values); on the contrary, linear regression values computed during the “approach” phase are bigger than 0 (excluding 1 values).

Starting from this consideration we developed a component of Magicmap that, at each instant, detects the strongest AP, computes the linear regression and, according also to the instantaneous signal strength values, estimates the user state (“Inside room”, “Depart”, “Approach”, “Outside room”).

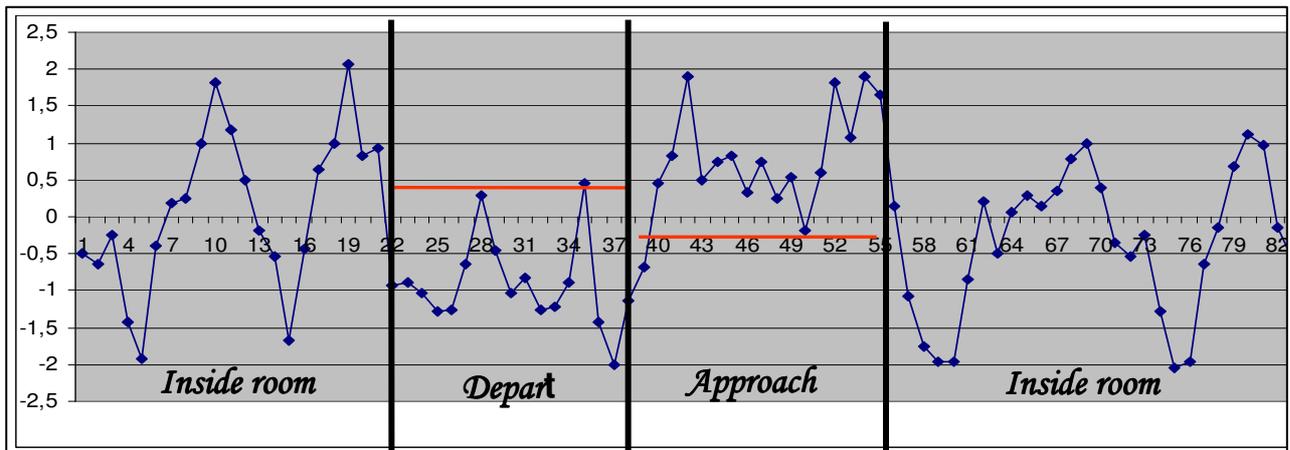


Figure 56: linear regression of that AP’s signal

3.4.2.2 Identification Algorithm

The identification algorithm is performed in two steps. To present the identification algorithm more formally, some definitions are required.

- $VTS_{items} = \{idV_1, idV_2, \dots, idV_{nVTS}\}$ is the set of targets detected by 3DTracker
 where $nVTS$ = number of actual detected targets
 idV_i = vector of the last 30 detections of the target I
- $WiFiP_{items} = \{idW_1, idW_2, \dots, idW_{nWF}\}$ is the set of clients tracked by Magicmap
 where nWF = number of Magicmap clients.
- idV_i .BirthTime is the instant in which 3DTracker detects a new target;
- idW_i . timeUnderDoor is the instant in which Magicmap detects that the user is under the door.

Given a client idW_i , the set of idV_i , $S_{idW_i} = \{idV_i, \dots, idV_{nVTS}\}$, that could be potentially associated with it is:

$$S_{idW_i} = \{ idV_i.BirthTime - idW_i.timeUnderDoor < \xi; idV_i \in VTS_{items} \ \& \ idV_i \notin S_{idW_i} \}.$$

The best $idV_i \in S_{idW_i}$ to be associated with idW_i is found as follow:

$$idV_{Best} = \{ \min (d(idV_i, AP_{position}) - d(idW_i, AP_{position})) \}$$

where

- $d(idV_i, AP_{position})$ is the Euclidean distance between the position of the target idV_i (x, y) and the position of the AP mounted over the door;
- $d(idW_i, AP_{position})$ is the distance calculated using the signal strength received by the AP mounted over the door applying the Motley-Keenan propagation model:

$$P_{received}(d) = P_{received}(d_0) - 10 * \alpha * \log(d/d_0)$$

where $P_{received}(d)$ is the signal strength received by the device at distance d;

$P_{received}(d_0)$ is the signal strength received by the device at distance d_0 ;

α is a coefficient modeling the radio wave propagation.

The proposed algorithm is able to automatically identify users that enter in the supervised room. Experimental tests show that to obtain a certain identification people needs to enter the room with delayed of almost 5 seconds.

The performance of the algorithm does not depend on the number of users that are inside the meeting room.

3.4.3 System Architecture

The identification-positioning application has been integrated in O3miscid, the Middleware for Pervasive Environment [Emonet et al.'06]. Figure 57 shows the overall architecture of the proposed system. On top of the basic full featured Java version of the

middleware, an OSGi version has also been built. The OSGi packages in the Java version expose a higher abstraction level interface that hides the technical details of the middleware. OSGi is essentially a service-oriented architecture for residential gateways. In this framework, any running component (known as *bundle*) exports the services it provides and it also can discover other services by means of a third role, the *OSGi Service Registry*. Being more precise, a bundle is a Java ARchive (JAR) representing the minimal component in OSGi that can be installed, uninstalled or updated. On another hand, the minimal unit of functionality is really what OSGi calls a service.

Three different bundles have been integrated in the O3miscid middleware to develop the proposed system:

1. **MagicMap Client (MMC)**: MMC is a O3miscid-compliant service that resides on the client device. This service has been developed to wrap the MagicMap client application with some added feature (it detects when the user approaches to an AP). When MMC starts, it downloads the conference plan, AP positions and RP information from the Magicmap Server.
2. **3DTracker Service (3DS)**: it resides on the server side. 3DS is able to detect all people in the meeting room but, as underlined above, it doesn't assign a unique identifier to tracked people.
3. **PositionIntegration Service (PosS)**: it resides on the server side and performs the identification algorithm.

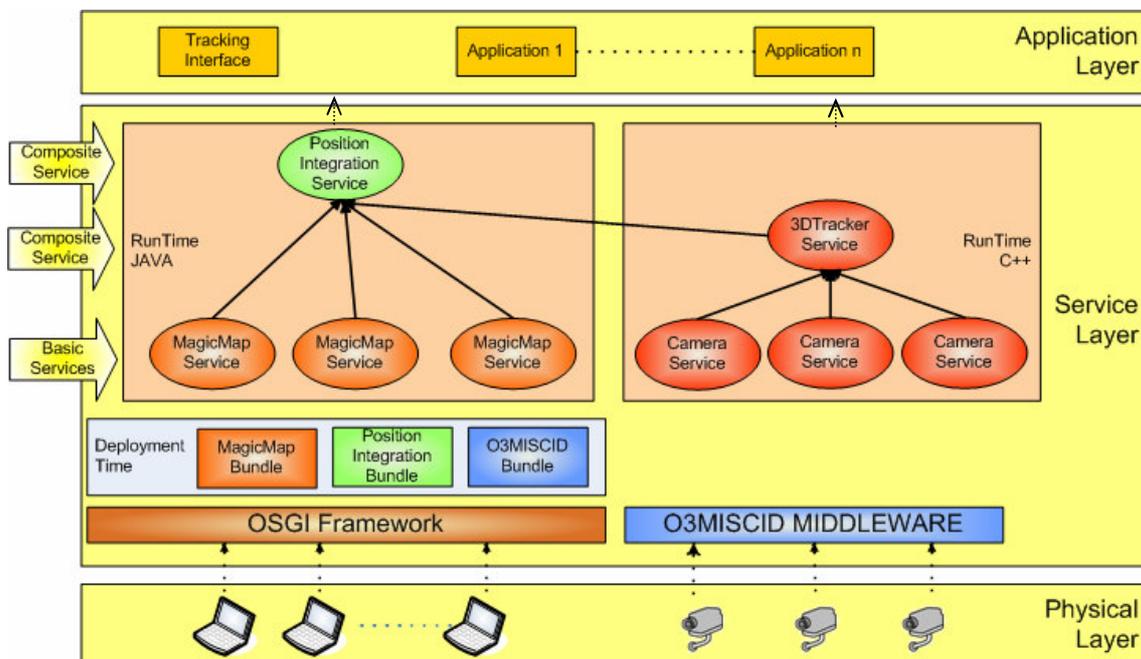


Figure 57: System Architecture

When the MMC detects that the client is approaching to the meeting room it starts the communication with PosS. In particular once the MMC detects that the client is “near” the entrance of the meeting room, it starts to send one message per second to PosS.

The XML message contains:

- the client ID,
- the time,
- the nearest AP,
- the client status (that could be “under the door” or “Inside the meeting room”).

The PosS will use this information together with the position of all the mobile targets estimated by the 3DS to perform the best association between the MMC client and the targets detected by the camera using the algorithm described in 3.4.2.2.

Figure 58 shows perceptual services and two higher level services. The 3DTacker service is responsible for tracking people in the room using two or more cameras (this tracker and more generally internal processing of services are not in the scope of this article).

MagicClient services running on each client device use Wifi card and determine if there is someone entering in the supervised room. The PoS takes outputs from previous services and performs reasoning to compute the user identification.

Figure 59 shows the application interface, in which on the left can be seen the devices detected by the VTS, Magicmap and the performed association, while on the right the MagicMap interface is visualized.

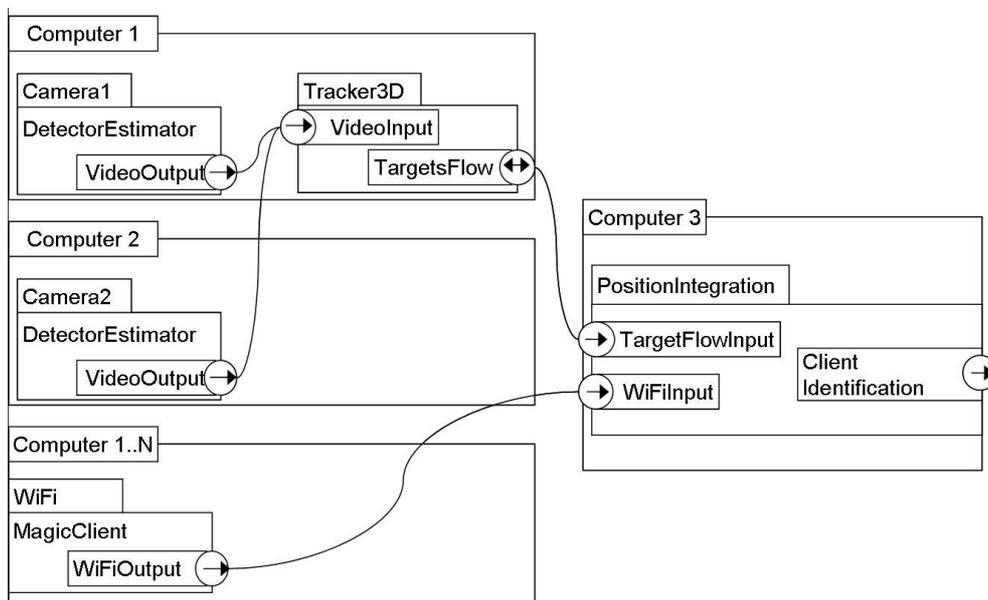


Figure 58: System Data Flow

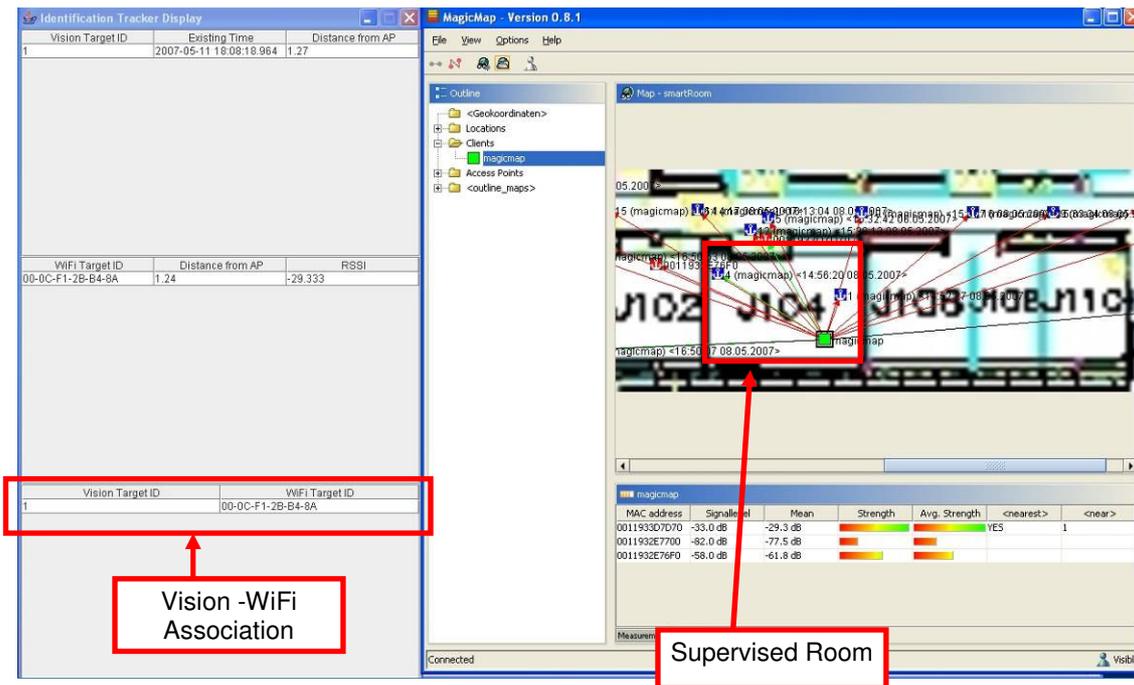


Figure 59: Application Interface

3.4.4 Evaluation and conclusions

The presented project is an indoor identification-positioning system that combines the strong identification provided by the WiFi tracking system with the high precision typical of the VTS, in order to obtain a continuous tracking system able to uniquely identify and track users. It allows the identification of people carrying WiFi enabled devices inside rooms equipped with cameras for accurate positioning.

The identification process required when the user enters the room is accurate when only one user is under the detection region. It does not depend on the detected object inside the room, but only on the number of users that simultaneously have to be identified. For example, if two clients are close to each other and need to be identified, the WiFi localization system is not able to understand which user is on the left and which one is on the right, resulting in an erroneous identification. In order to obtain an accurate result, users have to enter inside the meeting room with an interval between each other of at least 5 seconds.

This problem could be also noticed even if, instead of using WiFi, another technology, like BT, is used. On the contrary, using a very short range RFID system, this problem can be overcome.

The localization system could be improved, first of all by improving the precision and the reliability of the two applications used (MagicMap and 3DTracker). On one side MagicMap should be improved in order to reduce position error, considering that at the moment the

identification process does not use Magicamp algorithm, due to large errors. A better performance can be obtained modifying the infrastructure, placing APs in a better configuration, even if this solution is contrary to the principle of unobtrusiveness. Other approaches consist in using smart maps to detect allowable path, avoiding erroneous detected situations in which the user passes through walls.

On the other side 3DTracker should be improved in order to reduce false positive detections or the loss targets phenomenon.

At the moment the system has been implemented only for Windows XP.

Future work to be considered should be the activity recognition inside the meeting room. It is noteworthy that the 3DTracker is already able to detect user's activity. A similar approach could be tried with WiFi technology. When the user (with a Wifi enabled device) enters in the supervised room, using this algorithm he is automatically detected and identified. Inside the supervised room we could infer some user activities like:

- The user sits down and places the device close to him (typically on the table or on his knees);
- The user puts down the device and moves in the room.

Using the 3DTracker and Magicmap separately it is not possible to understand these situations. Comparing information provided by the two systems at the same instant we are able to infer some activities. In order to infer activities by WiFi signal strength, the approach used by John Krumm [Krumm et al.'04] has been analyzed. This system, called LOCADIO, uses WiFi signal strengths from existing APs measured on the client to infer states of "still" and "moving", by capturing the "jumpiness" of a time series of signals quantitatively by computing a temporally windowed, running sample variance of the received signal strength of the strongest AP at the given time. That is, at any given time, the AP with the strongest signal is detected and then the variance of that AP's signal over a short interval ending at the given time is computed. Comparing the WiFi still/motion information with the 3DTracker speed information it should be detected if the user is moving with or without device and if the 3DTracker has lost the target.

3.5 Considerations

The goal of this research was to provide user position with minimum level of intrusiveness in the environment, finding the best tradeoff between usability, unobtrusiveness and resolution, keeping in mind that in a museum it is normally impossible to introduce perturbation to its environmental and architectural balance.

Starting from the MSU, the wearable inertial sensing platform that compute position without requiring external infrastructure, two different systems have been integrated to initialize position and heading: the GPS for indoor environments and the VTS used indoors.

While GPS is completely unobtrusive, VTS needs to install at least one camera in the environment. It could be defined as intrusive, but its intrusiveness is compensated by the services that it can provide, very useful especially in museums, like the counting of the visitor and the video surveillance.

The MSU associated with the two calibration systems can continuously work both indoor and outdoor, without problems related to realignment, calibration or position and heading initialization.

The next step of this work is the seamlessly transition among the two proposed solutions. Placing the stereo camera in the entrance door of the indoor environment it is possible to detect the change of the model space (from indoor to outdoor or vice versa). In this way when the system detects that the user is entering by passing under the door the GPS receiver can be switched off and the PDRS can be calibrated with the VTS.

This thesis proposes also an indoor pedestrian identification and tracking system that combines the vision based tracking system, with the WiFi localization. The aim of this system is to provide a multi-resolution localization system, able to locate user with a higher resolution in rooms equipped with vision based tracking system and lower accuracy out of this room, taking advantages from WiFi infrastructure. Experiments conducted, however, reveal that the identification algorithm suffer from the low accuracy of WiFi localization, especially when more than one user needs to be identified simultaneously.

CHAPTER 4.

CIMAD - A Framework for context-aware applications

This chapter aims to demonstrate the central role of localization systems in providing contextual services to visitors and CH sites.

Tourist guides, on one hand, should provide multimedia content automatically, according to the device location and orientation. The key to providing a visitor with relevant information is knowing where they are, what they are looking at, what they know about, and what they are interested in. On the other hand, museum curators or site experts might be interested in monitoring the number of visitors within a particular area or tracking their trajectories for many reasons, like for example security, space allocation, visitor statistics or promotion of the museum itself, preferences.

For this purpose CIMAD, a framework whose goal is to ease the creation of context-aware applications (in the CH domain) developed by our research group is described. The importance of localization systems in CH domain is demonstrated by the number of integrated services that rely on user position and direction. Among these services some of the previous localization systems have been integrated.

4.1 Framework for context-aware applications

“A framework is a mechanism that promotes the reuse of the architectural design and the code. Consequently, the effort and time involved in the development of the context-aware applications is significantly reduced” [Rarau et al.'05]. Frameworks support the development of integrated and customized context-aware applications enabling developers with different levels of experience, to efficiently develop modular context-aware applications which are interoperable.

In the last decade a lot of context-aware applications, both in the CH domain and in others domains, were developed from scratch as stand alone applications, not intended to be reused in a modular fashion, implying a lack of reusability, but also a problem in communication and interoperability. Frameworks have been introduced to help developers in solving interoperability problems. A notable example of a framework for context-aware applications is the ContextToolkit [Dey et al.'01]. It supports context-aware computing, providing some

important abstractions, i.e. it abstracts context services as location service, from the sensors that acquire the necessary data to be delivered to the service. The Context-Toolkit consists of widgets, aggregators, and interpreters. The widgets gather context information from sensors and provide the interface. The aggregators aggregate context information, while the interpreters provide the inferred context to applications.

After the ContextToolkit, an increasing number of applications are being developed out of modular re-usable building blocks which are combined through a context infrastructure, i.e. [Winograd'01; Coutaz et al.'02].

The prototype framework called CIMAD (Figure 60) aims to use the modularity introduced in context-aware applications also to the CH area, allowing overlapping functionalities and context elements to be re-used. The big challenge of CIMAD is to speed up and simplify the development process of CH applications and services for visitors and archeological sites. Several services can be implemented, like registration services, visitor flow monitoring, visitor guiding with support for user orientation and content delivery. The range of supported services could be extended for example with tools for site survey and data acquisition. CIMAD aims also to support different types of devices with different technological characteristics, private owned PDAs and smart phones to guides provided by the museum.

CIMAD is based on previous gained experiences and lessons learned in the field of CH domain during the MUSE project [Roffia et al.'05]. It covers all the aspects of a context-aware application, from the sensor layer, to the application layer. The core of this framework is Mobicomp, a context management system developed by the University of Kent, discussed in section 4.1.1.1.

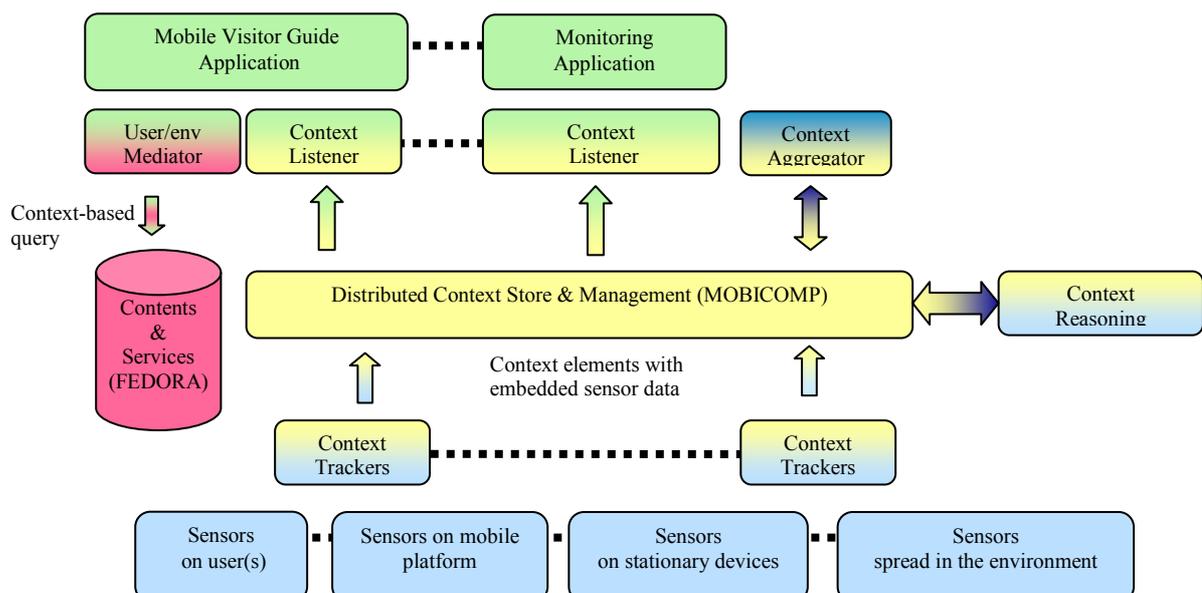


Figure 60: CIMAD Context-Aware Framework

The most widely used functionalities in CH applications are:

- User's context detection from sensors, with a focus on position detection.
- Dynamic adaptation of content, for example to device characteristics, user preferences and profile.
- Seamless data acquisition in fieldworks, for example with contextualization of notes and pictures.
- Context abstraction for detecting meaningful user states, for example walking or looking at a particular exhibit.

Through an extendable basis of modules for the most widely used functions, the overall goal of the common framework is enabling an efficient development of context-aware interoperable CH applications. Aiming to cater for the different levels of users ranging from archaeologists, museum curators to experienced developers is one of the biggest challenges of CIMAD. This challenge is confronted through a flexible structure, providing support and guidance at different levels. For inexperienced developers a number of high level modules are being made available which can be combined through the CIMAD application building process, enabling applications to be built based on existing modules and connected through a common infrastructure. By making an increasing number of such modules available, the number of possible applications and their level of sophistication will increase. Experienced developers on the other hand only have to comply to the guidelines set by the system architecture, in order to be able to integrate their modules with existing and future ones. This gives them the freedom to develop novel and advanced applications, generating modules and data that can be shared and reused.

One of the main applications that can be set up within CIMAD is a context aware visitor guide. As an example, the implementation process of a CIMAD interactive multimedia guide could look like the following:

- Cultural heritage specialists, i.e. museum curators or site experts, prepare the multimedia content and select the appropriate user interface.
- Curators prepare a "map component" associating each exhibit to its "context", e.g. physical location.
- Curators identify the criteria for organizing multimedia content into "thematic" or "geographic" tours.

The site management team together with the developers select the desired devices and technologies for delivering the guided visits, i.e. PDAs and location technology used. Based on the selected devices and technologies the developers construct the visitor guide.

4.1.1 CIMAD Architecture

In this section an implementation of a CIMAD architecture supporting the above mentioned framework is described. In order to provide services, CIMAD builds on top of two infrastructure components supported by EPOCH; they are the Fedora content management system and the MobiComp context management infrastructure. In addition, a CIMAD specific software interfacing component supporting access to MobiComp and Fedora, as well as parsing of configuration information, is provided.

In order to develop a CIMAD compliant application, the guidelines and the standards set by the components need to be followed. Below MobiComp, Fedora and the software interfacing component are described, followed by a description of the different states an application can be in.

4.1.1.1 Context Management: MobiComp

MobiComp is a context management infrastructure tailored to the needs of Cultural Heritage. Its core element is the ContextService (Figure 61), acting as a store for context information and providing the coordination between the components of context-aware applications. The storage components behind the ContextService interface can be configured to support different scales of context-aware applications: simple stand-alone applications, multiple applications on a single device and applications spanning multiple devices. In the last case, one or more networked servers make the context elements from heterogeneous sources accessible in a uniform way.

Context elements take the form of a subject-predicate-object triple, relating an entity identifier to a named context value. Three components exist for interacting with MobiComp: trackers, listeners and aggregators. A tracker is a MobiComp component that acts as a context producer. Trackers register their availability and capabilities by sending appropriate information to the ContextService. Their purpose is to collect raw context data from sensors, such as GPS receivers, MSU and VTS and other dynamic or static sources, including configuration files for device capabilities and user-preferences. Trackers transform their input into context elements which are then put into the tuplespace. A listener is a MobiComp component that receives notification of ContextEvents from the ContextService and performs some action based on the context element carried by the event object. They receive event notifications whenever a context element is put into or removed from the store. On receiving a notification, the listener may get the element from the store and use it as required.

An aggregator is a MobiComp component that combines the behaviour of both a tracker and a listener. Aggregators monitor events from the ContextService, rather than a sensor device,

and apply a transformation before returning a new element to the tuplespace. Aggregators can combine several low-level sensor elements to produce an element at a higher level of abstraction. For example, temperature, door, window and light sensor information might be used to determine room occupancy. Other aggregators may perform simple transformation services, i.e. converting latitude and longitude coordinates from a GPS sensor to coordinates on an appropriate local or national grid. Many non-trivial context-aware applications utilise a number of complex context aggregators, e.g. the FieldMap application described in [Van Leusen et al.'01].

To ease communication between infrastructure components, context elements are represented in the form of a XML document based on ConteXtML [Ryan'05], extending the subject-predicate-object triples. The elements carry a production timestamp, a default validity period, and a privacy level indicating how they may be disseminated through the ContextService.

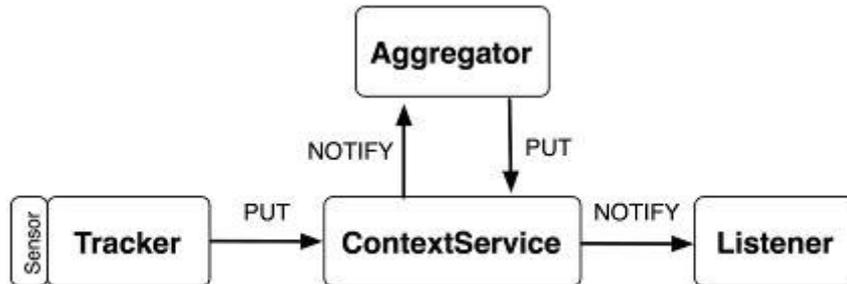


Figure 61: The Kent MobiComp infrastructure

```

<?xml version="1.0" encoding="UTF-8"?>
<context xmlns="http://www.mobicomp.orgConteXtML">
<contextElement privacy="public"
timestamp="2004-09-24T11:18:45" lifetime="600">
<subject>4da941681d39c92095e73fc59f2</subject>
<predicate>location.point</predicate>
<object type="SpatialObject">
<spatial srs="BNG" source="GPS"><point>
<x>553264.4</x><y>252387.3</y><z>98.3</z>
</point></spatial></object>
</contextElement>
    
```

Figure 62: ConteXtML

The object part of a context element may be arbitrarily complex, and different trackers might produce elements with similar names but different semantics. Equally, similar information may be packaged in different forms. Figure 62 shows a ConteXtML fragment

containing a location element, together with a timestamp, a lifetime, a privacy level and a unique entity ID.

The storage components behind the ContextService interface can be configured to support different scales of context-aware applications: simple stand-alone applications, multiple applications on a single device and applications spanning multiple devices. In the last case, one or more networked servers make the context elements from heterogeneous sources accessible in a uniform way.

4.1.1.2 Fedora content store and the Content Adaptation Layer

Fedora [CornellUniversity] is the content repository system used by the CIMAD architecture. In addition to the content repository, Fedora provides a collection of tools and interfaces for creating, managing, and disseminating “Fedora digital objects” (FDO) stored within the repository. A FDO allows the original format of an object to be stored, along with metadata, i.e. Dublin Core. Through format adaptation components it is possible to perform a format conversion of an FDO in real-time, allowing requests from external applications for a specific format to be satisfied, e.g. HTML, PDF and JPEG.

Fedora enables the multi-channel paradigm, by allowing FDOs which were produced once to be adapted at run time according to the user and device context. In Figure 60, the interaction of an application with Fedora is shown. The application publishes context on MobiComp through trackers and the CAL retrieves it through listeners. Once Fedora is aware of the context, it can provide the application with content which has been adapted based on the context.

4.1.1.3 Software interfacing component

The aim of the software interfacing component is to ease the development of context-aware applications and to enforce a number of guidelines. Through a single configuration description, possibly made public through MobiComp, the required Fedora and MobiComp components are instantiated with the correct parameters, allowing them to start the desired application. In addition, context information of the user and used device are associated with the application, taking away the burden of manually establishing the association between the different MobiComp elements. The configuration description, the user's context, as well as the device's context are formatted according to a CIMAD prepared XML-schema. Third party components, developed within the CIMAD community, can be made available through a central repository for future reutilization.

4.2 CIMAD developed services

A work in progress demonstration of CIMAD applications have been tested during the Interactive Salon, a touring exhibition, organized by EPOCH, about new technologies and concepts for communication with visitors, in the context of CH. Scenarios include both services for the visitors, archaeologists and managers of the CH site.

4.2.1 Museum Management Systems

CIMAD applications can be developed to support new approaches managing and accessing CH. The services demonstrated may be divided into two classes: services for Visitors and services for Museum Management.

4.2.1.1 Services for the Visitor – Visitor Guide

Guides are provided which use multimedia, context-aware mobile devices. Content may be provided automatically according to the device location and orientation, or manually by pressing keys. A visitor walking through the galleries obtains information about the exhibits as well as orientation support. Location and orientation on mobile devices may expand the capabilities of a system, make the user interface more effective and optimize the use of resources. The key to providing a visitor with relevant information is knowing where they are, what they are looking at, what they know about, and what they are interested in. Moreover the heterogeneity of devices must be considered: personal phones, PDAs or custom devices. All of them should be allowed to seamless access different services. Several different implementation of visitor guides based on various CIMAD componenets were proposed within EPOCH:

- Whyre, the purpose-built wearable guide system for Museums and archaeological sites. The version used in the StadMuseum automatically displays information about the exhibit the user is closest to and facing, for a detailed description please see Chapter 3. The MobiComp components used are the WHYRE dead reckoning location tracker, the VTS tracker to provide starting point and direction, or any other type of beacon tracker like for example RFID Tracker. Being location coordinates in different reference systems, a mechanism is realized by an aggregator able to convert between all reference systems used in museums scenario. An URL display listener is used to display content information.
- Two PDA based guides are used, one based on IR beacon tracker and the other on Wifi positioning. Both display information about the exhibit the visitor is standing next to, which is delivered to them by the URL display listener. The MobiComp

components used are the MagicMap Wifi location tracker or the IR beacon tracker, and the URL display listener.

- Personal devices, like PDA and smart phone of the visitor, that have an internet connection.
- A guide, based on computer vision components developed by colleagues of ETH, Zurich, that uses a conventional webcam to acquire images and present users with a viewfinder window [Bay et al.'05]. They use a camera tracker and the ETH Image recognition aggregator.
- A Semacode based guide that run on standard mobile phones with a built in camera and a GPRS connection – the guide is installed on the phone via a “Bluetooth Kiosk”. Visitors can take picture of semacodes situated to the exhibits they are interested in. A Semacode recognition aggregator is used to find and decode the semacode tag in the captured image.

Some of the developed services run on “any” PDA or Smartphone (e.g. Symbian or Windows mobile) provided with a web-browser. Other services run on a server and can be invoked by any client application, including web pages; they are meant to be used by context-aware applications to increase their functionality level, i.e. to decrease the “semantic gap” between the user and its environment. Other services rely on wearable sensor kits (for example PDRS and RFID readers, hired by the museum or archeological site. These services are interesting because they demonstrate that with significant impact that the knowledge of context can introduce in the application to increase its effectiveness. These services also show that occasionally, for performance or architecture reasons total separation between applications and data sources can not be achieved. Specifically our sensor driven guides need to read directly sensor data, so they are sensor dependent, while they would be fully separated by the sensor sources, if the sensor were a system resource (architectural issue) or if the MobiComp platform had a much higher bandwidth.

Developed services include:

- **Tracking and orienteering application:** the real-time positions of all visitors using a guide system inside the museum are displayed on a map of the Museum, including trajectories and visit durations. The locations are provided to the system by the visitor location listener. In addition to the real-time view, the system is used to analyze visitors’ behaviour and to identify “hot spots” inside the museum [Pettinari et al.'07]. Several localization technologies have been tested. The first kind of localization is based on the combination of PDRS with stereo vision cameras. The second localization system relies on the WiFi technology and uses the Magicmap application. Last but not the least a tracking visitor position using a combination of Inertial

Systems and RFID has been developed. The visitor uses the RFID “hot spot” as recalibration point, that are activated with a explicit request of the visitor.

- **Path Finder:** it helps the visitors of CH sites to find their way towards a desired destination, i.e. a specific exhibit, an emergency exit, the book shop. Path Finder finds the shortest path to get to a desired location, starting from a know location. If used in conjunction with a location system, it dynamically provides the direction to follow. Path Finder can be installed on a Web server (Path Finder-WS) or can be incorporated within a mobile application (Path Finder-EMB). It searches the shortest path basing on a data structure (specifically a graph) representing the entire area covered. The graph may be generated by an off-line Path Finder Remapping Utility, starting from a site map coded in a specific bitmap format.
- **Content Navigator:** it can be used solely on a device with a web browser and connectivity - not requiring any other user hardware or software. When the Content navigator is loaded on the user’s web browser, the browser parameters, i.e. the screen resolution, are determined automatically and are send to the server based content repository together with user preferences entered on the webpage. Once this data is received by the server, a disseminator is activated and the right content is provided to the user in the right format for the user’s device and displayed through the webbrowser. The content is adapted by Fedora, where it is stored as FDOs.
- **Context-aware navigator**, realised on a PDA and based localization system, displays information about the exhibit the visitor is standing next to. Considering for example the IR localization, the MobiComp components used for this guide are an IR beacon tracker and an URL display listener, in addition to an aggregator able to convert the IR beacon stream to a sequence of URLs, forming the "virtual path” of the visitor through the museum. The IR technology of this guide can be exchanged with RFID to create a guide which does not require line of sight.

4.2.1.2 Services for Museum Management

Three different services have been developed in the interest of the museum management: the visitors counting, the visitors registration and the visitor tracking.

Curators might be interested in monitoring the number of visitors within a particular area for many reasons, like for example security, space allocation or promotion of the museum itself. Monitoring information can be displayed on different devices, like for example fixed computer (for desk staff) or PDAs (for guardians), and can be stored to be processed offline later on.

4.2.1.2.1 Museum Presence Monitor

VTS described in Chapter 3 is able to detect the number of people that pass through a line. Data gathered by the VTS and stored on Mobicomp is used by the Museum Presence Monitor to provide real-time, as well as statistical information about the number of visitors currently in the exhibition and of the overall total number of visitors. The monitor application is notified by the visitor location tracker when a visitor enters or leaves the exhibition. Monitoring visitors' flow in museums, exhibitions, as well as in any location open to the public can be utilized by management personnel to adjust the site layout and to optimize the visit conditions in terms of visit quality and site protection. Once the stereo-camera systems are installed in locations where all the visitors need to go through when entering and exiting the monitored area – potentially a single location if entrance and exit coincide – the VTS keeps track of the amount of people entering and leaving the site over time. From this anonymous and unobtrusively collected data set, the management can be kept continuously updated with basic parameters about how many visitors are currently inside the exhibition, how many visitors entered during the day, how much time on average they spent in the exhibition, and the average hourly visitors rate. From the above parameters long term statistics about an exhibition can be derived for analysis and decision making purposes.

To demonstrate the above mentioned concept, a stereo-camera was deployed at the different exhibitions of the “Interactive Salon”. Here the particular event of the Stockholm's StadsMuseum from October '06 till the end of March '07 is reported. The camera was installed on the ceiling of a 2.2 meters wide corridor near the entrance of the exhibition, next to the exhibition entrance desk. The visitor were monitored for over four months, below results are presented and evaluated.

Figure 63 depicts some of the data collected daily. The example shows that the amount of visitors exceeds 180 people at the end of the day (top left), the visitors hourly rate has a peak of 98 visitors/hour around lunch time, the amount of people inside the exhibition has a peak of 18 people just after lunch and, the average visit time drops substantially when the visitor flow and the density inside the exhibition is very high. Figure 64 reports on a more typical exhibition day with less visitors (around 100 people), but with a better distribution through out the day. The visitors inside the exhibition never exceed 11 people and the average visit time is relatively high, indicating that the exhibits can attract the attention of individuals or groups for quite a long time. Figure 65 shows a set of graphs that may be used to evaluate and compare the patterns of visitors over multiple months. The month considered in Fig.11 is January 2007. The graph on the left shows the amount of visitors for every day the exhibition was open, providing an aggregated value exceeding 2300 visitors per month. The graph on the right shows an estimate of the daily average visit time.

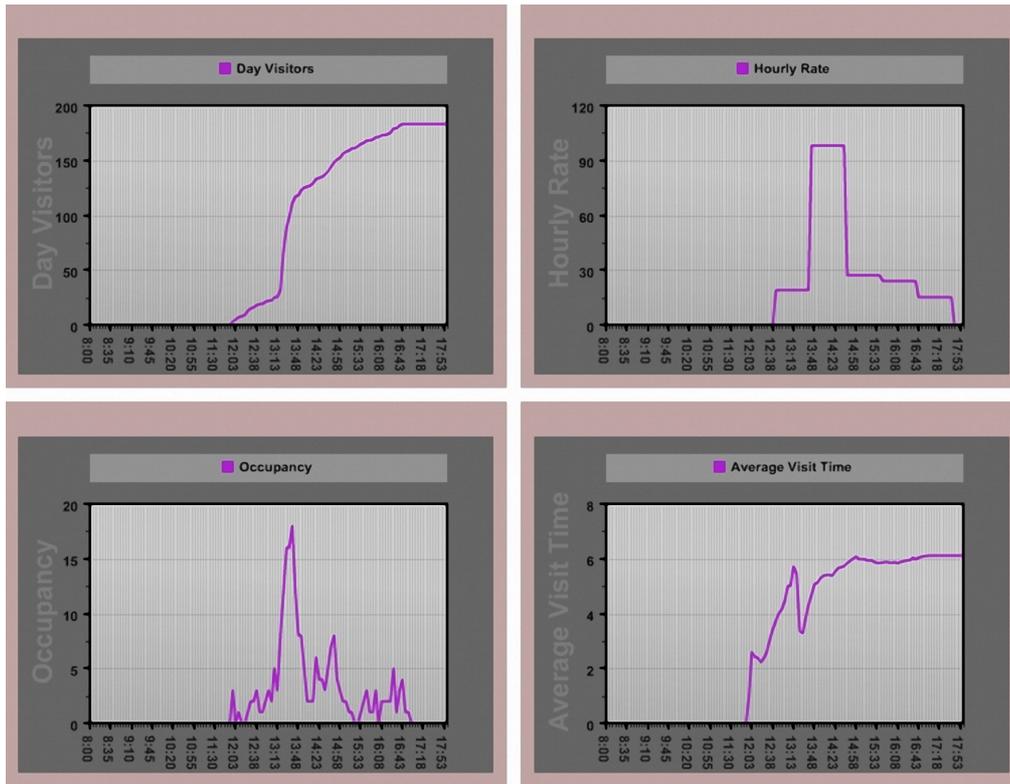


Figure 63: Museum Visitors Daily Statistics-1

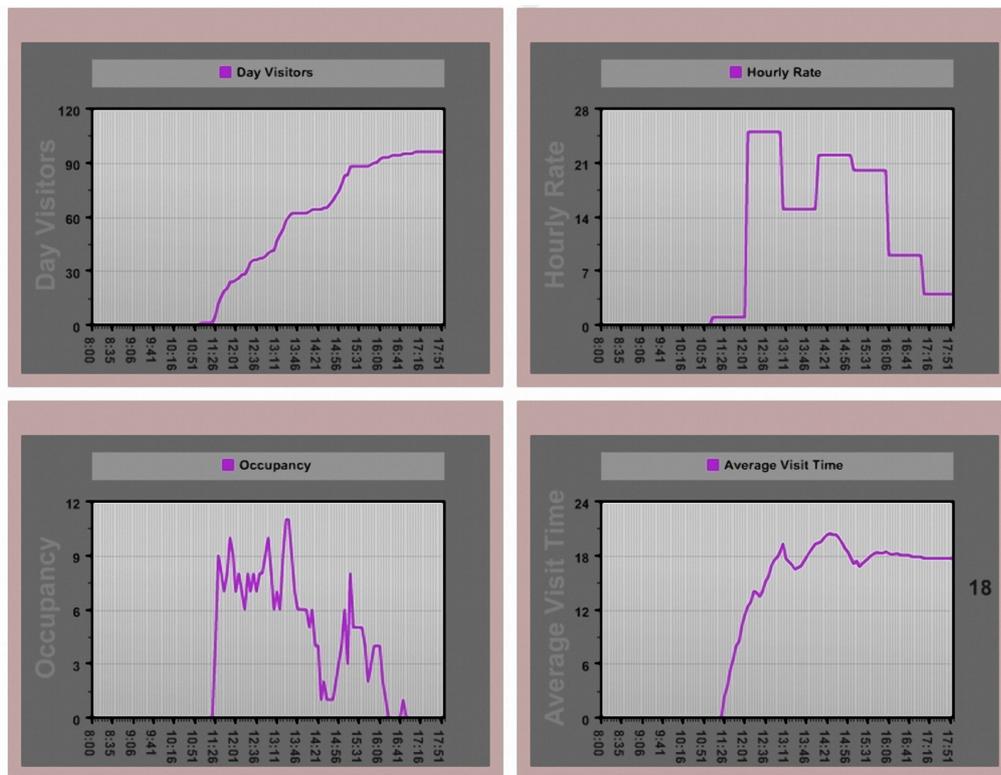


Figure 64: Museum Visitors Daily Statistics-2



Figure 65: Museum Visitors Monthly Statistic

This parameter has a large standard deviation since visit durations changes considerably with the visitor's profile. Evaluating the AVT standard deviation was not considered yet. Even though currently no quantitative analysis of the errors in the collected data set is available, the following errors sources may be mentioned:

- 1 – The system does not yet distinguish between staff and visitors;
- 2 – The system is jeopardized by staff members that do not go back the way they came;
- 3 – There may have some occasional reading error.

4.2.1.2.2 Museum Registration Desk

In order to provide a multimedia guide service, the museum staff must register each visitor that want to use a particular device. All the devices are stored (with their associated capabilities) into Mobicomp. During the registration process, the visitor chooses the desired device and fills a form with his or her preferences and some “privacy-free” data (age, sex, nationality). In this way the service can be suited to the user needs. As consequence of the registration, museum staff knows which are the used devices (and by who) and which are still available for the public. Furthermore, visitors who wish to use a context-aware guide can register with the MobiComp Museum Registration Desk application. The visitor's details are entered and the chosen guide is select. This information is made available to all applications through the ContextStore and also triggers the configuration of the chosen guide for this particular visitor. Visitors can remain anonymous or can sign up for post-visit online services.

4.2.1.2.3 Visitor Tracking System

The real-time information of all the visitors using a guide system inside the museum can be displayed on a map of the museum, including trajectory and visit durations. The locations are provided to the system by the visitor location listener.

4.3. Conclusions

The presented framework should help developers to design and create context-aware CH applications, providing a reusable approach. It is based on Mobicomp, a context management infrastructure that constitute the core of the framework, on Fedora, a content store, and on the Content Adaptation Layer.

It is evident that, in order to provide services to the visitor and to the site, one or more localization systems need to be integrated. Several example services for CH scenarios have been implemented and described, aiming to demonstrate how the technology can contribute to increase visibility and understanding of CH site.

The exploitation of guides and management systems in real world museums and sites, have convinced us that the CIMAD framework is highlighting the direction that needs to be taken in order to further expose the way that technology can be harnessed in facilitating how we access our CH, which in turn would be fruitful for Tourism as a whole.

CHAPTER 5.

CONCLUSIONS

The research discussed in this thesis was mainly carried out within the “mobile and ambient systems” workgroup of EPOCH, a 6FP Network of Excellence focused on harmonizing the use of IT in Cultural Heritage. Mission of the workgroup is to investigate technologies and methods to turn museums, sites and landscapes into smart environments, i.e. into ecosystems where interacting heterogeneous computing entities provide people with smooth services that are relevant to their particular situation. The set of properties that identify the situation are application dependent. One of the challenges considered by EPOCH is to define what the context is in applications running on cultural heritage sites, as well as finding methods to abstract such context as much as possible from the environment. Many of the relevant context elements in the addressed application area, including the environmental conditions, the technical specifications of the user device, the user situation, profile, preferences, and their location within the cultural heritage site, as related to the site exhibits and points of interest. This thesis focused on one primary element of the context - user’s location - and has tackled the following challenges:

- Locate and track users on a cultural heritage sites no matter whether indoors or outdoors;
- Find the best tradeoff between usability, unobtrusiveness and resolution, keeping in mind that in a museum it is normally impossible to alter the environmental and architectural balance;
- Make use of the same equipment, sensors and infrastructure used for location purposes, to abstract other context information, e.g. identify user activity from the accelerometers used for gyroscope compensations;
- Make use of location information for multiple, incremental services;
- Make positioning services platform inter operable, that they are available not only on specific devices, but making them platform independent.

Throughout the course of this research project several localization systems were considered.

The first localization research project is a pedestrian navigation system, that combines a wearable inertial sensing platform that estimates relative displacements using a dead reckoning approach, with absolute localization systems. The proposed system exploits two different

technologies to initialize and calibrate the sensing platform both in indoor and outdoor “difficult” environments.

For indoor environments a new hybrid localization system has been specifically developed, which is based on the co-operation between stereo vision based tracking and PDRS.

The mixed location system works switching between the PDRS and the stereo vision based tracking, according to the area the user is walking through. When the user goes through the monitored areas, the position is supplied only by the stereo vision based tracking, because of its high precision. Once it does not detect anymore the device, the position is provided by PDRS. Furthermore, the vision based tracking is used to initialize and periodically correct errors accumulated by the PDRS. Experimental results show that this kind of integration improves the reliability of the PDRS, reducing errors in position, direction and step length estimation, proving the feasibility of this approach. Further improvements should be done to obtain a fully automatic system, able to give reliable solutions in multi-user environments. In the meantime, the developed prototype adopts a semi automatic approach, that uses the explicit request performed by the user using well known “calibration area” placed under the camera, to execute the user identification. In this way no uncertainty is introduced, and the PDRS initialization and calibration are reliable.

The initialization and calibration of the wearable inertial sensing platform in outdoor environments has been realized developing a hybrid tracking system based on GPS. When signals from GPS are determined to be valid, GPS positions alone are used to track user, to initialize DR position and heading, and to correct DR step length parameter. When GPS signals are determined to be unreliable, the switching algorithm switches the system to positions determined by dead reckoning and ignores GPS. The integration of GPS with PDRS is not a new approach, but it well matches the unobtrusive requirements of the outdoor CH sites, exploiting satellite navigation. The developed approach however is less accurate if compared with the previous one, due to the lower accuracy of GPS than the vision based tracking system. Furthermore, in some conditions like urban canyon, GPS can have difficulties in computing position and consequently in initializing and calibrating the PDRS.

This two approaches provide a complete indoor/outdoor localization system, that exploits accurate PDRS, thank to a continuous calibration process.

The second localization research project is an indoor pedestrian identification and tracking system that combines the vision based tracking developed by the PRIMA-INRA research group, with the WiFi localization. The goal of the proposed system is to provide a multi-resolution localization system, able to locate user with a higher resolution in rooms equipped with vision based tracking system and lower accuracy outside, taking advantages from WiFi-based infrastructure. In particular the proposed system aims to univocally identify unknown user detected by the vision based system, exploiting Access Point signals. The

prototype implementation of this approach shows that the user identification is accurate if only one user is under the detection region. On the contrary, simultaneous multi-user identification provides very poor results.

The choice of WiFi localization was driven by the need to exploit already existing infrastructures and resources available on common device, like WiFi card. The poor accuracy achievable with WiFi localization approach, together with the single identification constraints suggest the use of an alternative technology to implement such an identification system, like for example a short range RFID. With short range RFID technology the user identification is straightforward, or however more reliable than the WiFi technology.

To conclude, localization of mobile users providing high degree of accuracy, wide coverage and no intrusiveness is a challenging task. Many localization systems have already been deployed in the last decades, but they are usually adapted to a particular space model, without supporting all the above requirements simultaneously. More work needs to be done in this direction to cope with all these issues and extend the ubiquitous usage of localization technology, as a first practical step towards the realization of the so long envisaged concepts of Smart Environments and Context Aware Computing.

As a representative example of this concept, CH domain has been used in this thesis, due to its innate need of technologies that could help people in better understanding the multifaceted cultural aspects of the world where we live. This thesis does not pretend to be a comprehensive research on localization systems applied to CH domain; however, addressing some of the issues related to their usage in real deployments, it aims to contribute in exploit the potential of using localization and, more broadly, context awareness as a key aspect in order to increase visibility and understanding of Cultural Heritage.

PUBLICATIONS

Raffa, G., Mohr, P. H., Ryan, N., Manzaroli, D., Pettinari, M., Roffia, L., Bartolini, S., Sklenar, L., Garzotto, F., Paolini, P., Salmon, C. T. (2007). "Cimad - a framework for the development of context-aware and multi-channel cultural heritage services". International Cultural Heritage Informatics Meeting (ICHIM07): Proceedings, Toronto, Archives & Museum Informatics.

Lamorte L., Licciardi C. , Marengo M., Salmieri A., Mohr P. H., Raffa G., Roffia L., Pettinari M., Salmon C. T. (2007) "A platform for enabling context aware telecommunication services", In: Proceedings of 3RD Workshop on Context Awareness for Proactive Systems (CAPS07), June 18-19, 2007, Guildford, United Kingdom, ISBN: 978-0-9556240-0-1

Raffa, G., Roffia, L., Pettinari, M., Nagaraj, R., Sforza, F. Mincoelli, G., Salmon C., T. (2007). "Context-aware computing for cultural tourism – experiences from the muse project". The Integration of Location Based Services in Tourism and Cultural Heritage, EPOCH Publication: 69-82.

Pettinari, M., Manzaroli, D., Bartolini, S., Roffia, L., Raffa, G., Di Stefano, L. Salmon Cinotti, T. (2007). "A stereo vision based system for advanced museum services". The Integration of Location Based Services in Tourism and Cultural Heritage, EPOCH Publication: 57-68.

Mohr P. H. Raffa G., Pettinari M., Salmon Cinotti T., Fr`a C., Venezia C., Protto P. (2007), "Towards context-aware Telecom end user services through SOA", In Proceedings of the 1st International Workshop on Telecom Service Oriented Architectures (TSOA 2007) at the 5th International Conference on Service-Oriented Computing, Vienna, Austria.

Salmon, C. T., Di Stefano L., Raffa G., Roffia L., Pettinari M., Mola M. (2006) "Dead reckoning supports stereo vision in pedestrians tracking", Proceedings of the 4th annual IEEE international conference on Pervasive Computing and Communications Workshops (PERCOM06), March 13-17, Pisa, Italy: 628-631.

Roffia L., Pettinari M., Raffa G., Gaviani G. (2005), "Context Awareness in Mobile Cultural Heritage Applications", In Proceeding of 7th International Conference on Ubiquitous Computing (UBICOMP05) Workshop on Smart Environments and their Applications to Cultural Heritage", September 11-14, Tokyo, Japan.



BIBLIOGRAPHY

- [Abowd et al.'97] Abowd, G., Atkeson, C., Hong, J., Long, S., Kooper, R. Pinkerton, M. (1997). "Cyberguide: A mobile context-aware tour guide." *Wireless Networks* 3(5): 421-433.
- [Abowd et al.'99] Abowd, G. D., Dey, A. K., Brown, P. J., Davies, N., Smith, M. Steggles, P. (1999). Towards a better understanding of context and context-awareness. Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing. Karlsruhe, Germany, Springer-Verlag.
- [ADXL202] ADXL202. Low-cost ± 2 g dual-axis accelerometer with duty cycle output. <http://www.analog.com/en/prod/0,2877,ADXL202,00.html>.
- [ADXRS150] ADXRS150. Gyroscope. <http://www.analog.com/en/prod/0,2877,ADXRS150,00.html>.
- [Aminian et al.'95] Aminian, K., Robert, P., Jequier, E. Schutz, Y. (1995). "Estimation of speed and incline of walking using neural-network." *Ieee Transactions on Instrumentation and Measurement* 44(3): 743-746.
- [Ancona et al.'99] Ancona, M., Dodero, G. Gianuzzi, V. (1999). Mobile computing in outdoor environments. Proceedings of the 1999 ACM symposium on Applied computing. San Antonio, Texas, United States, ACM.
- [Atairaerospace] Atairaerospace Gps-integrated imu. <http://www.atairaerospace.com/inu/>.
- [Bahl et al.'00a] Bahl, P., Balachandran, A. Padmanabhan, V. (2000a). Enhancements to the radar user location and tracking system.
- [Bahl et al.'00b] Bahl, P. Padmanabhan, V. N. (2000b). "Radar: An in-building rf-based user location and tracking system". INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE 2: 775-784 vol.2.
- [Battiti et al.'02] Battiti, R., Le Nhat, T. Villani, A. (2002). Location-aware computing: A neural network model for determining location in wireless lans.
- [Bay et al.'05] Bay, H., Fasel, B. Van Gool, L. (2005). "Interactive museum guide". In *Smart Environments and their Applications to Cultural Heritage*, EPOCH Publication.
- [Beauregard'07] Beauregard, S. (2007). "Omnidirectional pedestrian navigation for first responders". WPNC '07 Workshop on Positioning, Navigation and Communication: 3-36.
- [Beymer'00] Beymer, D. (2000). Person counting using stereo. Proceedings of the Workshop on Human Motion (HUMO'00), IEEE Computer Society.
- [Borkowski et al.'06] Borkowski, J. Lempi, J. (2006). "Practical network-based techniques for mobile positioning in umts." *EURASIP J. Appl. Signal Process.*(1): 149-149.

-
- [Brown'96] Brown, P. J. (1996). "The stick-e document: A framework for creating context-aware applications". Proceedings of EP'96, Palo Alto, also published in it EP--odd: 259-272.
- [Bruns et al.'07] Bruns, E., Brombach, B., Zeidler, T. Bimber, O. (2007). "Enabling mobile phones to support large-scale museum guidance." IEEE MultiMedia 14(2): 16-25.
- [Butz et al.'04] Butz, A., Jorg, B. Antonio, K. (2004). Augmenting buildings with infrared information, unknown.
- [Caporossi et al.'04] Caporossi, A., Hall, D., Reignier, P. Crowley, J. L. (2004). "Robust visual tracking from dynamic control of processing." Performance and Evaluation of Tracking and Surveillance PETS '04.
- [Castro et al.'01] Castro, P., Patrick, C., Ted, K. Muntz, R. R. (2001). A probabilistic room location service for wireless networked environments. Proceedings of the 3rd international conference on Ubiquitous Computing. Atlanta, Georgia, USA, Springer-Verlag.
- [Cavagna et al.'66] Cavagna, G. A. Margaria, R. (1966). "Mechanism of walking." Journal of Applied Physiology 21: 271-278.
- [Chen et al.'00] Chen, G. Kotz, D. (2000). A survey of context-aware mobile computing research, Dartmouth College.
- [Chen et al.'06] Chen, M., Sohn, T., Chmelev, D., Haehnel, D., Hightower, J., Hughes, J., Lamarca, A., Potter, F., Smith, I. Varshavsky, A. (2006). "Practical metropolitan-scale positioning for gsm phones". Ubicomp 2006: Ubiquitous computing: 225-242.
- [Cho et al.'02] Cho, S. Y., Park, C. G. I, J. G. (2002). "Measurement system of walking distance using low-cost accelerometers". ICCAS2003: 1799-1803.
- [Cloudcaptech] Cloudcaptech Integrated inertial sensors. <http://www.cloudcaptech.com>.
- [ClymerTech] ClymerTech Advanced sensing technologies. <http://clymer.cc>.
- [CornellUniversity] CornellUniversity Fedora digital repository system. University of Virginia. <http://www.fedora-commons.org/>.
- [Coutaz et al.'05] Coutaz, J., Crowley, J., L. , Dobson, S. Garlan, D. (2005). "Context is key." Commun. ACM 48(3): 49-53.
- [Coutaz et al.'02] Coutaz, J. Rey, G. (2002). "Foundations for a theory of contextors". CADUI 2002, May 15-17, Valenciennes, France.
- [Cutillo'06] Cutillo, L. (2006). "Calibrazione di un sistema di posizionamento inerziale mediante visione stereoscopica". Master Thesis, University of Bologna
- [Damala et al.'07] Damala, A., Marchal, I. P., H. (2007). "Merging augmented reality based features in mobile multimedia museum guides". XXI International CIPA Symposium, 01-06 October 2007, Athens, Greece.
- [Dana'00] Dana, P. H. (2000) "Global positioning system overview." DOI:

-
- [Darrell et al.'00] Darrell, T., Gordon, G., Harville, M. Woodfill, J. (2000). "Integrated person tracking using stereo, color, and pattern detection." *Int. J. Comput. Vision* 37(2): 175-185.
- [De Angelis'05] De Angelis, A. (2005). "Studio di assetto con accelerometri triassiali", University of Bologna
- [Dey et al.'01] Dey, A., Salber, D. Abowd, G. (2001). A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications.
- [Di Stefano et al.'02] Di Stefano, L., Marchionni, M., Mattoccia, S. Neri, G. (2002). "A fast areabased stereo matching algorithm". 15th IAPR/CIPRS International Conference on Vision Interface, Calgary, Canada.
- [DIGO'02] DIGO. (2002). Defense imagery and geospatial organization. <http://www.defence.gov.au/digo/>.
- [Djuknic et al.'01] Djuknic, G. M. Richton, R. E. (2001). "Geolocation and assisted gps." *Computer* 34(2): 123-125.
- [Doucet et al.'01] Doucet, A., De Freitas, N. Gordon, N. e. (2001). "Sequential monte carlo in practice". New York, Springer-Verlang.
- [Eberspacher et al.'01] Eberspacher, J. Vogel, H.-J. (2001). "Gsm switching, services and protocols", John Wiley & Sons, Inc.
- [Ekahau] Ekahau Inc., 2005, ekahau positioning engine 3.1. <http://www.ekahau.com/>.
- [Elrod et al.'93] Elrod, S., Hall, G., Costanza, R., Dixon, M. Rivi, J. D. (1993). "Responsive office environments." *Commun. ACM* 36(7): 84-85.
- [Emonet et al.'06] Emonet, R., Vaufreydaz, D., Reignier, P. Letessier, J. (2006). "O3miscid: An object oriented opensource middleware for service connection, introspection and discovery". 1st IEEE International Workshop on Services Integration in Pervasive Environments.
- [EPOCH] EPOCH European research network on excellence in processing cultural heritage. <http://www.epoch-net.org/>.
- [Estrin et al.'02] Estrin, D., Culler, D., Pister, K. Sukhatme, G. (2002). Connecting the physical world with pervasive networks. 01: 59-69.
- [Evannou'07] Evannou, F. (2007). "Technique et technologies de localisation avancées pour terminaux mobiles dans les environnements indoor", Université Joseph Fourier
- [Ferrer-Biosca et al.'07] Ferrer-Biosca, A. Lux A. (2007). A visual service for distributed environments: A bayesian 3d person tracker.
- [Feuerstein et al.'89] Feuerstein, M. Pratt, T. (1989). " A local area position location system". *Mobile Radio and Personal Communications, 1989.*, Fifth International Conference on, Coventry, UK: 79-83.
- [Foresti et al.'06] Foresti, L., Bolognesi, A. Gilli, F. (2006). "Arianna: A gps-wifi enabled multimedia guide for tourists visiting art cities". *Mobile Guide 06, Turin-Italy*.

-
- [Fox et al.'00] Fox, D., Thrun, S., Dellaert, F. Burgard, W. (2000). "Particle filters for mobile robot localization". New York, Springer Verlag.
- [Foxlin'05] Foxlin, E. (2005). "Pedestrian tracking with shoe-mounted inertial sensors." IEEE Comput. Graph. Appl. 25(6): 38-46.
- [Fyfe'99] Fyfe, K. R. (1999). Motion analysis system. United States Patent, No. 5,955,667.
- [GALILEO] GALILEO European satellite radio navigation system
http://ec.europa.eu/dgs/energy_transport/galileo/index_en.htm
- [Garzotto et al.'03] Garzotto, F., Cinotti, S. Pigozzi, M. (2003). "Designing multi-channel web frameworks for cultural tourism applications: The muse case study". In Proc. of Museums and the Web Conference, Charlotte (VG), Archives and Museum Informatics.
- [Gigl et al.'07] Gigl, T., Janssen, G. J. M., Dizdarevic, V., Witrisal, K. Irahhtauten, Z. (2007). "Analysis of a uwb indoor positioning system based on received signal strength". Positioning, Navigation and Communication, 2007. WPNC '07. 4th Workshop on, Hannover: 97-101.
- [Goertz et al.'04] Goertz, M., Ackermann, R., Schmit, J. Steinmetz, R. (2004). "Ontext-aware communication services: A framework for building enhanced ip telephony services". International Conference on Computer Communications and Networks (ICCCN) 2004: 535-540.
- [Graumann et al.'03] Graumann, D., Hightower, J., Lara, W. Borriello, G. (2003). "Real-world implementation of the location stack: The universal location framework" 0: 122.
- [Grewal et al.'93] Grewal, M. Andrews, A. (1993). "Kalman filtering : Theory and practice". Englewood Cliffs, New Jersey, Prentice-Hall.
- [Günther et al.'05] Günther, A. Hoene, C. (2005). "Measuring round trip times to determine the distance between wlan nodes." Networking 2005.
- [Harada et al.'03] Harada, T. U., H., Mori, T. Sato, T. (2003). "Portable orientation estimation device based on accelerometers, magnetometers and gyroscope sensors for sensor network." Proceedings of IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems, MFI2003. : 191- 196.
- [Harter et al.'99] Harter, A., Hopper, A., Steggle, P., Ward, A. Webster, P. (1999). The anatomy of a context-aware application. Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking. Seattle, Washington, United States, ACM.
- [Harville'04] Harville, M. (2004). "Stereo person tracking with adaptive plan-view templates of height and occupancy statistics." Image and Vision Computing 22: 127-142.
- [Hazas et al.'04] Hazas, M., Scott, J. Krumm, J. (2004). "Location-aware computing comes of age." Computer 37(2): 95-97.
- [Hightower et al.'01] Hightower, J. Borriello, G. (2001). "Location systems for ubiquitous computing." IEEE Computer 34(8): 57-66.
- [Hightower et al.'00] Hightower, J., Want, R. Borriello, G. (2000). "Spoton: An indoor 3d location sensing technology based on {rf} signal strength." (00-02-02).

-
- [Hitachi] Hitachi Hitachi airlocationtm, a wireless lan based location detection system. <http://www.hitachi-cable.co.jp/en/infosystem/news/20031119la.html>.
- [Ho et al.'06] Ho, W., Smailagic, A., Siewiorek, D. P. Faloutsos, C. (2006). An adaptive two-phase approach to wifi location sensing. Proceedings of the 4th annual IEEE international conference on Pervasive Computing and Communications Workshops, IEEE Computer Society.
- [Holux] Holux. Receiver. <http://www.holux.com/JCore/en/home/index.jsp>.
- [Hsi'04] Hsi, S. (2004). "I-guides in progress: Two prototype applications for museum educators and visitors using wireless technologies to support science learning". The 2nd IEEE International Workshop on Wireless and Mobile Technologies in Education, 2004. Proceedings.: 187- 192.
- [Hull et al.'97] Hull, R., Neaves, P. Bedford-Roberts, J. (1997). "Towards situated computing". ISWC '97: Proceedings of the 1st IEEE International Symposium on Wearable Computers, IEEE Computer Society.
- [Ibach et al.'05] Ibach, P., Stantchev, V., Lederer, F., Weiß, A., Herbst, T. Kunze, T. (2005). "Wlanbased asset tracking for warehouse management". IADIS International Conference e-Commerce, Porto, Portugal: 15-17.
- [Intersense] Intersense. Inertiacude2. <http://www.isense.com/product/prec/ic2/index.htm>.
- [Jiravimut et al.'03] Jiravimut, P., Jiravimut, R., Ptasinski, P., Shah, M. A., Garaj, V., Cecelja, F. Balachandran, W. (2003). "A method for dead reckoning parameter correction in pedestrian navigation system." IEEE Transactions on Instrumentation and Measurement 52(1): 209 - 215.
- [Jirawimut et al.'03] Jirawimut, R., Ptasinski, P., Garaj, V., Cecelja, F. Balachandran, W. (2003). " A method for dead reckoning parameter correction in pedestrian navigation system." Instrumentation and Measurement, IEEE Transactions on 52(1): 209- 215.
- [Judd'97] Judd, T. (1997). "A personal dead reckoning module". ION GPS-97, Kansas City, Missouri.
- [JUNG'06] JUNG (2006). Java universal network / graph framework. <http://jung.sourceforge.net>.
- [Kalman'60] Kalman, R. (1960). "A new approach to linear filtering and prediction problems." Transactions ASME Journal of Basic Engineering: 35-44.
- [Kaplan'96] Kaplan, E. (1996). "Understanding gps: Principles and applications", Artech House.
- [Kindberg et al.'01] Kindberg, T. Barton, J. (2001). "A web-based nomadic computing system." Comput. Networks 35(4): 443-456.
- [King'98] King, A. D. (1998). "Inertial navigation -- forty years of evolution." GEC Review 13(3): 140.149.
- [KMZ51] KMZ51. Magnetometer. <http://www.semiconductors.philips.com/pip/KMZ51.html>.
- [Korkea-Aho'00] Korkea-Aho, M. (2000). Context-aware applications survey - report. <http://www.hut.fi/~mkorkeaa/doc/context-aware.html>.
-

-
- [Kotanen et al.'03] Kotanen, A., Hännikäinen, H., Leppäkoski, T. Hämäläinen, T. D. (2003). Experiments on local positioning with bluetooth. Proceedings of the International Conference on Information Technology: Computers and Communications, IEEE Computer Society.
- [Krumm et al.'04] Krumm, J. Horvitz, E. (2004). "Locadio: Inferring motion and location from wi-fi signal strengths". Mobile and Ubiquitous Systems: Networking and Services, 2004. MOBIQUITOUS 2004. The First Annual International Conference on: 4-13.
- [Krumm et al.'03] Krumm, J. Platt, J. (2003). Minimizing calibration effort for an indoor 802.11 device location measurement system.. I. T. R. MSR-TR-2003-82, Microsoft Research.
- [Kupper'05] Kupper, A. (2005). "Location-based services: Fundamentals and operation", John Wiley & Sons.
- [Ladetto'00] Ladetto, Q. (2000). "On foot navigation : Continuous step calibration using both complementary recursive prediction and adaptive kalman filtering". Proc. of ION GPS: 1735-1740.
- [Ladetto et al.'00] Ladetto, Q., Gabaglio, V., Merminod, B., Terrier, P. Schutz, Y. (2000). "Human walking analysis assisted by dgps". Global Navigation Satellite System, GNSS, Edinburgh, Scotland.
- [Ladetto et al.'02] Ladetto, Q. Merminod, B. (2002). "Digital magnetic compass and gyroscope integration for pedestrian navigation". 9th Saint Petersburg International Conference on Integrated Navigation Systems, Saint Petersburg, Russia.
- [Laitinen et al.'01] Laitinen, H., Lahteenmaki, J. Nordstrom, T. (2001). " Database correlation method for gsm location". Vehicular Technology Conference, 2001. VTC 2001 Spring. IEEE VTS 53rd, Rhodes, Greece 4: 2504-2508.
- [Lamarca et al.'04] Lamarca, A., Chawathe, Y., Consolvo, S., Hightower, J., Smith, I., Scott, J., Sohn, T., Howard, J., Hughes, J., Potter, F., Tabert, J., Powledge, P., Borriello, G. Schilit, B. (2004). Place lab: Device positioning using radio beacons in the wild.
- [Lang et al.'02] Lang, P., Ribo1, M. Pinz, A. (2002). "A new combination of vision-based and inertial tracking for fully mobile, wearable, and real-time operation". 26th Workshop of the AAPR/OAGM, Graz, Austria: 141 - 148.
- [Lee et al.'02] Lee, J.-Y. Scholtz, R. A. (2002). "Ranging in a dense multipath environment using an uwb radio link." Selected Areas in Communications, IEEE Journal on 20(9): 1677- 1683.
- [Leppakoski et al.'02] Leppakoski, H., Kappi, J., Syrjarinne, J. Takala, J. (2002). "Error analysis of step length estimation in pedestrian dead reckoning". ION GPS, In Proceeding Of, Portland.
- [Lester et al.'05] Lester, J., Choudhury, T., Kern, N., Borriello, G. Hannaford, B. (2005). "Untitled". International Joint Conference on Artificial Intelligence (IJCAI).
- [Levi et al.'99] Levi, R. W. Judd, T. (1999). Dead reckoning navigational system using accelerometer to measure foot impacts. U.S. Patent. No. 5,5583,776.
- [Liu et al.'06] Liu, X., Corner, M. D. Shenoy, P. (2006). "Ferret: Rfid localization for pervasive multimedia." UbiComp 2006.

-
- [Luinge et al.'04] Luinge, H. J. Veltink, P. H. (2004). "Inclination measurement of human movement using a 3-d accelerometer with autocalibration." *Neural Systems and Rehabilitation Engineering*, IEEE Transactions on 12(1): 112-121.
- [Malavasi et al.'00] Malavasi, M., Sforza, F. Salmon Cinotti, T. (2000). "On site cultural heritage discovery and fruition with muse: A mobile multimedia interactive system". VAST Euroconference, Oxford, Virtual archaeology: 231-234.
- [Mäntyjärvi et al.'06] Mäntyjärvi, J., Paternò, F. Salvador, Z. S., C. (2006). Scan and tilt: Towards natural interaction for mobile museum guides. Proceedings of the 8th conference on Human-computer interaction with mobile devices and services. Helsinki, Finland, ACM.
- [Masakatsu et al.'03] Masakatsu, K. Takeshi, K. (2003). Personal positioning based on walking locomotion analysis with self-contained sensors and a wearable camera. Proceedings of the The 2nd IEEE and ACM International Symposium on Mixed and Augmented Reality, IEEE Computer Society.
- [Matos et al.'06] Matos, R., Santos, D. F. Sanguino, J. E. R., A. (2006). "A gps-based mobile coordinated positioning system for firefighting scenarios". *Mobile Computing and Wireless Communication International Conference, 2006. MCWC 2006. Proceedings of the First, Amman*: 209-214.
- [Mei-Hsuan et al.'06] Mei-Hsuan, L. Tsuhan, C. (2006). "Cmuseum: A location-aware wireless video streaming system". *IEEE International Conference on Multimedia and Expo*: pp. 2129-2132.
- [MEMS] MEMS. <http://www.memsnet.org/>.
- [Microstrain] Microstrain. Inclinometers and orientation sensors. <http://www.microstrain.com>.
- [Miller'03] Miller, L. E. (2003). Why uwb? A review of ultrawideband technology. Report to NETEX Project Office.
- [Murai et al.'07] Murai, Y. T., H. Miyakawa, M. (2007). "A haptic walk-guide simulator for the visually impaired - a prototype -". *Systems, Man and Cybernetics, 2007. ISIC. IEEE International Conference on, Montreal, QC, Canada*: 3731-3736.
- [Muzii et al.'03] Muzii, R., Varlese, V., Pezzullo, A., Bile, U., Salmon, C. T., Raffa, G., Roffia, L., Taboni, C., Galasso, S., Malavasi, M., Sforza, F. Spinoso, A. (2003). "A wearable and interactive multimedia device reveals the memories of the city at "La certosa di san martino" In napoli". *Cultural Institutions and digital Technology, Ecole du Louvre, Paris, Archives & Museum Informatics*.
- [Nec-Tokin] Nec-Tokin 3d motion sensor. <http://www.nec-tokin.com/>.
- [Ni et al.'04] Ni, L. M., Yunhao, L., Yiu Cho, L. Abhishek, P. P. (2004). "Landmarc: Indoor location sensing using active rfid." *Wirel. Netw.* 10(6): 701-710.
- [Nick et al.'99] Nick, R., Jason, P. David, M. (1999). *Fieldnote : A handheld information system for the field*.
- [O-Navi] O-Navi. Inertial sensor technology. <http://www.o-navi.com/>.
- [OmniInstruments] OmniInstruments. Inertial measurement units. <http://www.omniinstruments.co.uk/>.
-

-
- [Oppermann et al.'00] Oppermann, R. Specht, M. (2000). "A context-sensitive nomadic exhibition guide". HUC '00: Proceedings of the 2nd international symposium on Handheld and Ubiquitous Computing, Springer-Verlag: 127-142.
- [Otsason et al.'05] Otsason, V., Varshavsky, A., Lamarca, A. de Lara, E. (2005). "Accurate gsm indoor localization". UbiComp 2005: Ubiquitous Computing: 141-158.
- [Pascoe et al.'99] Pascoe, J., Ryan, N. Morse, D. (1999). Issues in developing context-aware computing. Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing. Karlsruhe, Germany, Springer-Verlag.
- [Patwari et al.'05] Patwari, N., Ash, J., Kyperountas, S., Hero, A. O., Moses, R. M. S., C. N. (2005). "Locating the nodes: Cooperative localization in wireless sensor networks." IEEE Signal Processing Magazine 22(4): 54-69.
- [Pettinari et al.'07] Pettinari, M., Manzaroli, D., Bartolini, S., Roffia, L., Raffa, G., Di Stefano, L. Salmon Cinotti, T. (2007). "A stereo vision based system for advanced museum services". The Integration of Location Based Services in Tourism and Cultural Heritage, Budapest, EPOCH Publication: 57-68.
- [Philipose et al.'03] Philipose, M., Fishkin, K., Fox, D., Kautz, H. P., D. Perkowski, M. (2003). "Guide: Towards understanding daily life via autoidentification and statistical analysis". In Proc. of the Int. Workshop on Ubiquitous Computing for Pervasive Healthcare Applications (Ubihealth).
- [Porretta et al.'04] Porretta, M., Nepa, P., Manara, G., Giannetti, F., Dohler, M., Allen, B. Aghvami, A. H. (2004). "A novel single base station location technique for microcellular wireless networks: Description and validation by a deterministic propagation model." Vehicular Technology, IEEE Transactions on 53(5): 1502 - 1514.
- [Pospischil et al.'02] Pospischil, G., Umlauf, M. Michlmayr, E. (2002). Designing lol@, a mobile tourist guide for umts. Proceedings of the 4th International Symposium on Mobile Human-Computer Interaction, Springer-Verlag.
- [Priyantha'05] Priyantha, N. (2005). "The cricket indoor location system ". PhD Thesis, Massachusetts Institute of Technology
- [Priyantha et al.'00] Priyantha, N., Chakraborty, A. Balakrishnan, H. (2000). "The cricket location-support system". MobiCom '00: Proceedings of the 6th annual international conference on Mobile computing and networking, ACM Press: 32-43.
- [Raffa'05] Raffa, G. (2005). "Context aware computing in smart environment ". PhD Thesis, University of Bologna
- [Raffa et al.'07a] Raffa, G., Mohr, P. H., Ryan, N., Manzaroli, D., Pettinari, M., Roffia, L., Bartolini, S., Sklenar, L., Garzotto, F., Paolini, P. Salmon, C. T. (2007a). "Cimad - a framework for the development of context-aware and multi-channel cultural heritage services". International Cultural Heritage Informatics Meeting (ICHIM07): Proceedings, Toronto, Archives & Museum Informatics.
- [Raffa et al.'07b] Raffa, G., Roffia, L., Pettinari, M., Nagaraj, R., Sforza, F. Mincoelli, G. S. C., T. (2007b). "Context-aware computing for cultural tourism – experiences from the muse project". The Integration of Location Based Services in Tourism and Cultural Heritage, Budapest, EPOCH Publication: 69-82.

-
- [Rantakokko et al.'07] Rantakokko, J., Handel, P., Eklof, F., Boberg, B., Junered, M., Akos, D., Skog, I., Bohlin, H., Nereg, F., Hoffmann, F., Andersson, D., Jansson, M., Stenumgaard, P. (2007). Positioning of emergency personnel in rescue operations possibilities and vulnerabilities with existing techniques and identification of needs for future. T. r. R&D, Royal Institute of Technology. Stockholm.
- [Rarau et al.'05] Rarau, A. Puszta, K. S., I. (2005). "Software framework for building context-aware applications using multifacet items". Second International Workshop on Software Aspects of Context (IWSAC'05), Santorini, Greece.
- [RDCM-802] RDCM-802 Geosensory. Digital compass module
<http://www.geosensory.com/rdcM-802.htm>
- [Renaudin et al.'07] Renaudin, V., Yalak, O. Tomé, P. (2007). "Hybridization of mems and assisted gps for pedestrian navigation." Inside GNSS January/February: 34-42.
- [Richard'98] Richard, B. (1998). Rtk gps. GPS World Advanstar Communication Inc
- [Rodden et al.'98] Rodden, T., Cheverst, K., Davies, N. Dix., A. (1998). "Exploiting context in hci design for mobile systems". Workshop on Human Computer Interaction with Mobile Devices, Glasgow.
- [Rodriguez et al.'05] Rodriguez, M., Pece, J. P. Escudero, C. J. (2005). In-building location using bluetooth. T. Report, Universidade da Coruna.
- [Roetenberg et al.'05] Roetenberg, D., Luinge, H., Baten, C. Veltink, P. (2005). "Compensation of magnetic disturbances improves inertial and magnetic sensing of human body segment orientation." IEEE transactions on neural systems and rehabilitation engineering 13(3): 395-405.
- [Roffia'04] Roffia, L. (2004). "Context related information sharing and retrieval in mobile cultural heritage applications". PhD Thesis, University of Bologna
- [Roffia et al.'05] Roffia, L., Pettinari, M., Raffa, G. Gaviani, G. (2005). "Context awareness in mobile cultural heritage applications". Workshop on Smart Environments and their Applications to Cultural Heritage (UbiComp05), Tokyo 33-36.
- [Roffia et al.'06] Roffia, L., Pettinari, M., Raffa, G. Salmon, C. T. (2006). "wpan effectiveness for sensors-based activity recognition". Demonstration Session of 4th Annual IEEE International Conference on Pervasive Computing and Communications (PERCOM06). Pisa
- [Roman et al.'04] Roman, G.-C., Julien, C. Payton, J. (2004). A formal treatment of context-awareness. In Proc. 7th International Conference Fundamental Approaches to Software Engineering (FASE), Springer: 12-36.
- [Roos et al.'02] Roos, T., Myllymaki, P., Tirri, H., Misikangas, P. Sievanen, J. (2002). "A probabilistic approach to wlan user location estimation." International Journal of Wireless Information Networks 9(3): 155-164.
- [Royaltek] Royaltek Gps receiver. <http://www.royaltek.com>
- [Ryan'05] Ryan, N. (2005). "Smart environment for cultural heritage". Reading historical spatial information from around the world: Studies of culture and civilization based on geographic information systems data. T. UNO. Kyoto, Japan, International Research Center for Japanese Studies.
-

-
- [Ryan et al.'05] Ryan, N., Salmon Cinotti, T. Raffa, G. (2005). "Smart environments and their applications to cultural heritage". Proceedings of a workshop held in conjunction with UbiComp'05, Tokyo, Japan, Archaeolingua, Budapest, Hungary.
- [Salber et al.'99] Salber, D., Dey, A. Abowd, G. (1999). The context toolkit: Aiding the development of context-enabled applications. CHI '99: Proceedings of the SIGCHI conference on Human factors in computing systems, ACM Press: 434-441.
- [Salmon et al.'06] Salmon, C. T., Di Stefano, L., Raffa, G., Roffia, L., Pettinari, M. Mola, M. (2006). Dead reckoning supports stereo vision in pedestrians tracking. Proceedings of the 4th annual IEEE international conference on Pervasive Computing and Communications Workshops, IEEE Computer Society.
- [Salmon et al.'01] Salmon, C. T., Malavasi, M., Romagnoli, E., Sforza, F. Summa, S. (2001). "Muse: An integrated system for mobile fruition and site management". ICHIM01. International Cultural Heritage Informatics Meeting, Milano: 609-621.
- [Salmon et al.'04] Salmon, C. T., Nagaraj, R., Mincolelli, G., Sforza, F., Raffa, G. Roffia, L. (2004). "Whyre: A context-aware wearable computer for museums and archaeological sites". 8th IEEE International Symposium on Wearable Computers (ISWC2004), Arlington, Virginia: 174-175.
- [Schilit et al.'94] Schilit, B., Norman, A. Want, R. (1994). "Context-aware computing applications". {IEEE} Workshop on Mobile Computing Systems and Applications, Santa Cruz, CA, US.
- [Segvic et al.'03] Segvic, S. Slobodan, R. (2003). "A software architecture for distributed visual tracking in a global vision localization system". Computer Vision Systems, Third International Conference, ICVS, , Graz, Austria, Springer 2626: 365-375.
- [SiRF] SiRF Binary protocol manual. www.usglobalsat.com/downloads/SiRF_Binary_Protocol.pdf
- [Skyhook] Skyhook Wifi positioning. <http://www.skyhookwireless.com/howeare/news07.php>.
- [Spasojevic et al.'01] Spasojevic, M. Kindberg, T. (2001). A study of an augmented museum experience. HPL-2001.
- [Stork] Stork, T. Electronic compass design using kmz51 and kmz52. http://www.semiconductors.philips.com/acrobatdownload/applicationnotes/AN00022_COMPASS.pdf, Philips Semiconductors, Germany.
- [Sugano et al.'06] Sugano, M., Kawazoe, T., Murata, M. Ohta, Y. (2006). "Indoor localization system using rssi measurement of wireless sensor network based on zigbee standard". In Proc. Of The IASTED International Conference on Wireless Sensor Networks (WSN 2006), Banff (Canada).
- [Sutherland'02] Sutherland, D. H. (2002). " The evolution of clinical gait analysis - part ii kinematics". Gait and posture, Isevier, 16.
- [Syrjärinne'01] Syrjärinne, J. (2001). Wireless-assisted gps keeping time with mobiles. GPS World: 22-31.
- [Tenmoku et al.'04] Tenmoku, R., Kanbara, M. Yokoya, N. (2004). "A positioning method combining specification of user's absolute position and dead reckoning for wearable augmented reality systems". Proc. IEEE CREST/ISWC '04 (Workshop on Advanced

-
- Computing and Communicating Techniques for Wearable Information Playing), Arlington, VA.
- [TI] TI Texas instruments. <http://www.ti.com>
- [Titterton et al.'04] Titterton, D. Weston, J. (2004). "Strapdown inertial navigation technology - 2nd edition".
- [Topaz] Topaz Location system. <http://www.tadlys.com/>.
- [Tortoriello'04] Tortoriello, A. (2004). "Un modulo multisensore per piattaforme mobili". Master Thesis, University of Bologna
- [Ubisense] Ubisense Real time localization system, . <http://www.ubisense.net>.
- [Van Leusen et al.'01] Van Leusen, M. Ryan, N. (2001). "Educating the digital field-work assistant". Computer application and quantitative methods in archeology conference, Gotland.
- [Varshavsky et al.'05] Varshavsky, O. V., LaMarca, A. De Lara, A. (2005). "Accurate gsm indoor localization". Ubicomp, Springer 3660 141--158.
- [Vectronix] Vectronix. Inertial measurement units. <http://www.vectronix.com/>.
- [Vlahakis et al.'01] Vlahakis, V., Karigiannis, J., Tsotros, M., Gounaris, M., Almeida, L., Stricker, D., Gleue, T., Christou, J., T. , Carlucci, R. Ioannidis, N. (2001). Archeoguide: First results of an augmented reality, mobile computing system in cultural heritage sites. Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage. Glyfada, Greece, ACM.
- [Wang et al.'07] Wang, H.-P. Wang, Y.-K. (2007). "The research on indoor location system based on cricket". Machine Learning and Cybernetics, 2007 International Conference on, Hong Kong, Chin 5: 2662-2666.
- [Want et al.'92] Want, R., Hopper, A., Falc, V. Gibbon, J. (1992). "The active badge location system." ACM Trans. Inf. Syst. 10(1): 91-102.
- [Warrior et al.'03] Warrior, J., McHenry, E. McGee, K. (2003). " They know where you are [location detection]." Spectrum, IEEE 40(7): 20-25.
- [Weinberg'02] Weinberg, H. (2002). Using the adxl202 in pedometer and personal navigation applications. APPLICATION NOTE,, Analog Devices.
- [Weiser'91] Weiser, M. (1991). "The computer for the twenty-first century." Scientific American 3: 94-104.
- [Winograd'01] Winograd, T. (2001). "Architectures for context. In human-computer interaction." In Human-Computer Interaction 16(2): 401-419.
- [Woodman'07] Woodman, O. J. (2007). An introduction to inertial navigation Technical report UCAM-CL-TR-696, University of Cambridge.
- [Xiang et al.'04] Xiang, Z., Song, S., Chen, J., Wang, H., Huang, J. Gao, X. (2004). "A wireless lan-based indoor positioning technology." IBM J. Res. Dev. 48(5/6): 617-626.
- [XSens] XSens Motion technologies. <http://www.xsens.com>.
-

-
- [Yedavalli et al.'05] Yedavalli, K., Krishnamachari, B., Ravula, S. Srinivasan, B. (2005). Ecolocation: A sequence based technique for rf localization in wireless sensor networks. Proceedings of the 4th international symposium on Information processing in sensor networks. Los Angeles, California, IEEE Press.
- [Yilmaz et al.'06] Yilmaz, A., Javed, O. Shah, M. (2006). "Object tracking: A survey." ACM Comput. Surv. 38(4): 13.
- [Youssef et al.'05] Youssef, M. Agrawala, A. (2005). The horus wlan location determination system. Proceedings of the 3rd international conference on Mobile systems, applications, and services. Seattle, Washington, ACM.
- [Youssef et al.'02] Youssef, M., Agrawala, A., Shankar Noh, S. (2002). A probabilistic clustering-based indoor location determination system.
- [Zambonelli'05] Zambonelli, L. (2005). "Sistema di riconoscimento di attivita' per navigatori personali". Master Thesis, University of Bologna
- [Zhao'02] Zhao, Y. (2002). "Standardization of mobile phone positioning for 3g systems." Communications Magazine, IEEE 40(7): 108-116.
- [Zimmermann et al.'07] Zimmermann, A., Lorenz, A. Oppermann, R. (2007). "An operational definition of context". Modeling and using context: 558-571.