POLITECNICO DI TORINO

Scuola di dottorato - SCUDO

Dottorato in Ingegneria Informatica e dei Sistemi – XVIII ciclo

Tesi di Dottorato

Enhancing the museum experience with a sustainable solution based on contextual information obtained from an on-line analysis of users' behaviour

Jetmir Xhembulla

Tutore
Prof. Giovanni Malnati

Coordinatore del corso di dottorato
Prof. Matteo Sonza Reorda

Marzo 2016

Summary

Human computer interaction has evolved in the last years in order to enhance users' experiences and provide more intuitive and usable systems. A major leap through in this scenario is obtained by embedding, in the physical environment, sensors capable of detecting and processing users' context (position, pose, gaze, . . .). Feeded by the so collected information flows, user interface paradigms may shift from stereotyped gestures on physical devices, to more direct and intuitive ones that reduce the semantic gap between the action and the corresponding system reaction or even anticipate the user's needs, thus limiting the overall learning effort and increasing user satisfaction. In order to make this process effective, the context of the user (i.e. where s/he is, what is s/he doing, who s/he is, what are her/his preferences and also actual perception and needs) must be properly understood. While collecting data on some aspects can be easy, interpreting them all in a meaningful way in order to improve the overall user experience is much harder. This is more evident when we consider informal learning environments like museums, i.e. places that are designed to elicit visitor response towards the artifacts on display and the cultural themes proposed. In such a situation, in fact, the system should adapt to the attention paid by the user choosing the appropriate content for the user's purposes, presenting an intuitive interface to navigate it. My research goal is focused on collecting, in a simple, unobtrusive, and sustainable way, contextual information about the visitors with the purpose of creating more engaging and personalized experiences.

The world is like a ride in an amusement park, and when you choose to go on it you think it's real because that's how powerful our minds are. The ride goes up and down, around and around, it has thrills and chills, and it's very brightly colored, and it's very loud, and it's fun for a while. Many people have been on the ride a long time, and they begin to wonder, "Hey, is this real, or is this just a ride?" And other people have remembered, and they come back to us and say, "Hey, don't worry; don't be afraid, ever, because this is just a ride. . .

Bill Hicks

Acknowledgements

It has been three years now and this very fast and rich journey has come to an end. First of all I would like to thank my family and my little sister for all the sacrifices and struggles that they have endured for me to be here today.

A very special and sweet thank you goes to Eni, the sunrise of these five years. *Me D*.

I would like to say thank you to all the cousins and friends for the nice nights, the travels, the PES games, and the many evenings spent together. Last, but not least I would like to thank you, even though not enough, the friends with whom I spent almost every day in the last three years in the Appeal Laboratory.

Faleminderit! Jetmir

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Museums, and in general cultural heritage sites, can be defined as educational leisure settings. Visitors roaming in these venues are there for many different reasons. Some of them have come into a museum to spend some free time there instead of exploring a shopping mall. On the other hand there are visitors who are art/history/geography experts and have come at the museum to continue a learning path that existed before entering the museum. In either case the outcome of a museum visit is knowledge and learning. It can be something totally new or just a refinement of what already was known by the individual. These two different kinds of visitors come to the museum with exactly the same purpose: learning. It is just the "amount and/or shape" of what was learned that is different. And there can be many more categories depending on the chosen selection criteria: some of us are neither experts nor novices. Nevertheless all these different visitors experience the museum in their own personal way and thus need a digital tool that can adapt to their peculiarities in order to maximize the outcome of such an experience. It can be seen as some sort of "personal museum assistant" that "understands" who we are and provides us information tailored to our needs and expectations.

1.1 Problem definition

Location-based systems currently represent a suitable solution to enhance cultural experiences inside museums, since they can satisfy visitors' needs through the provision of contextualized contents and services. The use of a mobile digital tool during the visit definitely discloses new opportunities for contextual learning scenarios.

Multimedia interactive guides are rapidly replacing the old-fashioned audio and textual guides in city and museum tours. Nowadays, the availability of low-cost and powerful consumer mobile devices, providing rich interaction with a large variety of multimedia contents, and the availability of fast wireless communication networks are boosting the appearance of mobile applications dedicated to supporting tourist mobility . The increasing potential provided by mobile guides has been underlined by several surveys [11, 45, 73, 113]. Their functionalities cover a wide range of services aiming at helping users to create meaningful connections with both physical and digital environments. Through the use of context-aware mobile applications supporting the visit, museums can turn into pervasive learning environments, where the bridging of the objects of the real world with a virtual environment by means of mobile tools can contribute to the learning process [82]. Additionally, the adoption of gamification techniques that integrate game elements in non-gaming systems to improve user engagement [38] may represent an effective way to involve specific target audiences, fostering their attention and interest.

At this stage of research, the main barriers that still limit the potential of mobile learning are not technological but social, and concern the understanding of the contexts in which mobile resources are used [53]. As suggested by authors, in a mobile learning scenario mobility does not only refer to the technology but also to the learner [142]: the learner not only interacts with the devices in specifically situated physical and social contexts, but these interactions generate new contexts that may ultimately affect the learning process.

The learning process tends to be highly subjective and varies with time. A visitor does not have the same focus he/she had at the beginning of his/her visit after two hours. As Bitgood defines in [16] "visitor attention is a group of psychological and physiological processes that involve a continuum of three-stages (capture, focus, and engage) with each stage sensitive to a unique combination of independent variables ". This must be taken into account when designing a museum assistant system.

Museum guides can bee seen as very specialized digital personal assistants, with the most modern being Apple's Siri, Google's Google Now and Microsoft's Cortana [1], that try to infer what are your needs and interests in a certain moment. Being able to understand who you are and what you might be interested in at a certain moment in time and at a particular location is not an easy task. Google Now, for example, provides, among other functionalities, information about the traffic and the weather every day in the morning as you are ready to leave home towards work. How is this achieved? The system understands

[1]Google Now, Siri and Cortana are the latest iterations of the corresponding company's personal assistants and are available on their mobile devices.

that you leave around the same time every day towards the same place. The same situation is being repeated almost continuously permitting the software to understand that this is something you do frequently and thus transforming it into a clue on who you are and how do you behave in relation to this specific need.

Applying the same process to a museum visit is unfeasible because we do not visit the same museum with the same frequency as we go to work, school, or even the pub we go to on a Friday evening. It becomes much more difficult for a museum assistant software to understand who we are and what we might like. While tendencies and behaviors of visitors can be analyzed with the purpose of finding common patterns, identifying these patterns involves many aspects of a museum tour:

- total time of the visit
- time spent on particular artworks
- sequence at which these items are explored
- skipped artworks

Customization, based on personal needs and behavior, in such scenario is extremely challenging, especially since for most of the visitors the visit could be their first and last one. It is the case of tourists' for example. A user model is necessary, and this model has to be flexible and powerful enough to make it possible to identify behavioral patterns quickly and in an unobtrusive manner. Studies have been carried on this regard and it has been shown that even though prediction is not always consistent it is possible to understand the visitors type [79]. Ethno-methodologists Veron and Levasseur [143] propose a model for classifying visitors in four categories based on their movements inside cultural venues.

Provided a model the next step is to fit actual visitors into this model. A possible solution is to submit them a form or an interview in order to identify their type. These explicit data provide relevant information about who the users might be, but could be biased by users who will be somehow judging themselves. The analysis of their behavior in an indirect form tends to be more impartial and could lead to more accurate results for the model fitting purposes. Another great advantage of implicit analysis is that it could be achieved in a totally anonymous form as the goal of the system is to identify who the user is in the proposed model and not to identify or "spy" visitors.

Tracking visitors' movements inside cultural venues makes it possible to fit them in the aforementioned [143] classification although the task is not simple and presents several issues that will be further discussed in chapter 5.

The first part of my PhD was focused towards understanding how visitors learn in museums and what motivates during these experiences. I participated in the design, development and assessment stages of three mobile museum applications, two of which in the form of location based games. These experiments were designed with the purpose of verifying how contextually aware applications could help foster engagement and learning in visitors. The data analysis of the aforementioned applications, with the purpose of identifying common visitor behavior patterns, highlighted that the indoor positioning system being used was not enough to identify visiting styles. This was mainly due either to location information being too coarse-grained (room level accuracy) or because there were some periods of time in any visit where it was impossible to know where the visitor was while doing those actions since she/he had pointed a marker several minutes earlier. These conclusion highlighted the relevance of the indoor positioning/tracking solution in analyzing visitor behaviors. The second part of my PhD was then focused towards the study of existing indoor positioning solutions and the design and prototyping of a new reliable and unobtrusive indoor positioning/tracking system based on Bluetooth Low Energy technology.

1.2 Outline of this Thesis

Chapter 2 of this thesis is dedicated to the process of museum learning (how and why do people learn in museums) and the relevance of context in this process. Chapter 3 describes the experiments that were conducted at the Palazzo Madama Museum to assess the effectiveness of context-aware mobile guides in a cultural heritage site. Two of these experiments targeted young visitors: two mobile location-aware games were designed with the goal of understanding how and if unconventional stimuli could help young visitors learn and enjoy their visit. Chapter 4 is focuses ont the study of indoor positioning technologies and finally chapter 5 describes the Bluetooth Low Energy positioning system that I eventually designed and developed.

Chapter 2

Background

The role of museums as institutions that communicate tangible and intangible heritage for the purposes of education, study and enjoyment of society is universally recognised. More specifically, museums can be defined as either non-formal or informal learning environments, depending on the circumstances related to the visit:

- structured educational activities led by museum staff and addressed to specific target audiences (i.e. schoolchildren, teachers, families, artists) make museums non-formal learning environments [44]

- informal learning environments, since the stimuli intentionally provided by museums through different media may inspire the learning process of audiences visiting the institution in their free-time

We will focus on the informal learning aspect of the museum experience. Informal learning is the most common type of learning that takes place in museums because most of the visitors go through the experience without a human guide and thus have only paperback books or their knowledge to rely on for the meaning making process. To understand the works in display these visitors can not rely only on their intuition or knowledge. An art expert might feel at home in a paintings gallery but he most surely will not be so much at ease in a science exposition. The same could happen the other way, but this does not mean that with the proper "tools" the engineer can not enjoy the art gallery. The "proper tool" in this case could be an adaptive museum guide that understands who the visitor is and adapts it's contents in order to match the visitors' skills levels. By doing this, adapting to different kinds of needs and skills the guide could make the whole experience more interesting and appealing. This could, in turn, result into a higher engagement during the visit and thus leading to a better and more profitable experience.

The Contextual Model of Learning

But how and why does learning occur in a museum? How do museums motivate visitors to learn? Many scholars have tried to answer this question. One of such theories states that the learning process facilitated by the museum environment can be explained with the Contextual Model of Learning. It has been proposed by J. H. Falk and L. Dierking [48]. According to this model, learning is a process where meaning is actively constructed by the learner [62]; in this process, the personal context of the learner, the socio-cultural context supporting the visit and the physical context of the museum play important roles. The personal context of the learner includes the visitors interests, skills, previous experiences and background, which ultimately result in her or his understandings about the objects and information on display; the social context mainly refers to the interaction of the visitor with his or her companions, the museum staff and other visitors, whereas the physical context refers to the characteristics of the environment the visitor moves through, the exhibits and the interpretative tools provided by the institution [115]. The Contextual Model of Learning suggests that 12 key factors result influential in museum learning experiences [46]:

- Personal context:
  - Visit motivation and expectations
  - Prior knowledge
  - Prior experiences
  - Prior interests
  - Choice and control
- Sociocultural context:
  - Within group social mediation
  - Mediation by others outside the immediate social group
- Physical context:
  - Advance organizers

- Orientation to the physical space
- Architecture and large-scale environment
- Design and exposure to exhibits and programs
- Subsequent reinforcing events and experiences outside the museum

The social and physical contexts play an important part in the museum learning experience but the personal context is the real driver behind learning. It is also the most easily measurable and exploitable for the purpose of a better visit. Analysis of the personal context makes it possible to understand how to keep a visitor in a state of flow during the whole visit.

Flow and Intrinsic motivations

In his work "Flow and the psychology of discovery and invention" [33] Csikszentmihalyi introduces the concept of flow. Flow is defined as "*a state in which people are so involved in an activity that nothing else seems to matter; the experience is so enjoyable that people will continue to do it even at great cost, for the sheer sake of doing it*[32]."

The state of flow is achieved when these three conditions are achieved:

- the activity must have a clear set of goals and progress
- the task at hand must have clear and immediate feedback
- one must have a good balance between challenges and skills. Confidence in own abilities is needed to complete the task

If the above conditions are met then, during the activity as the skill level increases altogether with the challenge level the state of flow is achieved. In this state of the user has control over the activity while enjoying it at the same time. Csikszentmihalyi's flow model is presented in figure 2.1.

Csikszentmihalyi analyzes the museum experiences and tries to answer the question of why does one want to learn. His conclusion is that intrinsic motivation is the key factor when it comes to this informal learning scenarios. One of the main drivers of intrinsic motivation are curiosity and interest. We are all curious but not at the same level about the same things.

The museum role regarding to this aspect is to arouse our interests by using the works in display as a "hook" [34] and the same could be done by a mobile guide that understands

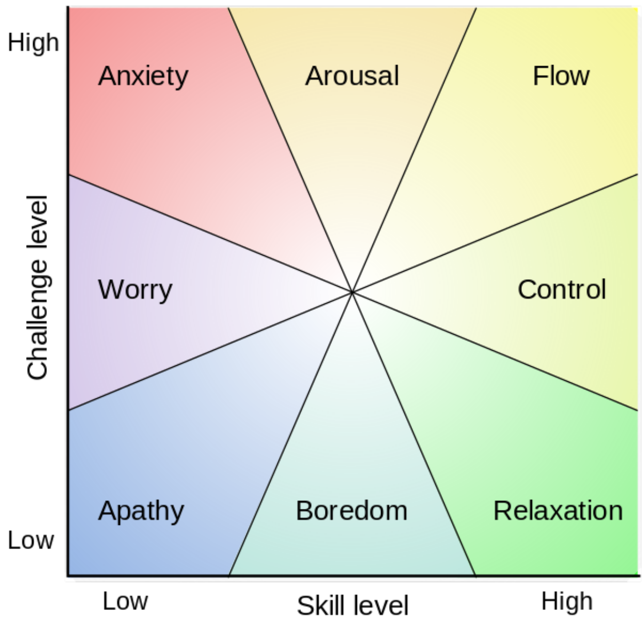


Figure 2.1: Mental state in terms of challenge level and skill level, according to Csikszentmihalyi's flow model. Image from https://en.wikipedia.org/wiki/Flow_(psychology).

what this visitor might like based on what he has been interested up until now. This motivational hooks are essential to attract interest but are not enough to keep the state of flow. After attracting curiosity the guide should also present information suited to that particular visitor in order to keep the user's attention. It must "engage sustained interest in order for the learning to take place" [34].

Mobile learning

Whilst interpretative tools have been traditionally represented by labels, panels, low-tech interactives and, more recently, by fixed touch screens and audio guides, the spreading of mobile technologies, taking advantage of the portability, connectivity and multimediality of devices such as smartphones and tablets, is now facing museums with new opportunities, introducing them to a mobile learning scenario.

For the purposes of this thesis, mobile learning will be defined as "a form of informal learning where the learner traverses a physical context carrying a personal mobile device which provides learning materials and activities" [76]. In this framework, a branch that may suit the special characteristics of learning in museums is pervasive learning, since it takes into account not only a specific physical context, but also the time, activities and actors within the context. Considering that ”pervasive learning environments create a bridge from the real world to the virtual world, allowing the context-sensitive utilization of real-world objects and information in the learning process” [76], mobile learning seems thus a promising solution for cultural institutions such as museums, which largely base their activity on the display of objects. The attempt of effectively providing educational leisure experiences that leverage on visitors attitudes towards learning for fun has become a common scenario in the museum field [105, 106] and will be discussed in 2.3.2.

Nowadays most of us possesses a mobile device, powerful enough to execute rich interactive applications. These hand-held devices have become powerful enough to fully replace personal computers, have almost always access to the Internet and are all the time in our pockets or bags. We are familiar with them and rely on them for accessing information in many moments of our daily routines. Mobile guides accessed through these devices fall in the area of location based systems if they exploit also the current user position to select the contents being offered to the user.

Contents are one of the main aspects for these guides, and thus they have to be properly designed and communicated to address the characteristics, interests and curiosity of the museum audiences [77, 114, 73, 45]. In other words, each type of target audience requires a specific language and different insights to suit its features, a relevant aspect which has been underestimated in several approaches. The key to provide personalized access to the museum contents is exploiting contextual information to develop adaptive mobile guides. Examples are the Hippie project [102], where user’s location as well as personal interests, knowledge and preferences are used to choose alternative paths inside the museum and to select the appropriate content to be presented, and the PEACH project [133], where a user model is automatically built while the user moves inside the museum and then used to adapt the displayed content and suggest additional elements of interest. Another interesting example is the CHIP interactive tour guide in the Rijksmuseum [117].

Adaptive museum guides can also take into account, as contextual parameter, the users’ visit styles and derive recommendation algorithms from them. Visiting style models categorize visitors according to criteria such as route followed, dwell time per exhibit and number of stops inside the museum.

On this basis, authors have proposed several classifications [37, 131, 128]. For instance, visitors’ visiting patterns have been compared to different animal behaviors, identifying the ant, fish, butterfly and grasshopper styles [143]. The Experimedia BLUE project [90] uses this model and fits users into the latter by using a virtual museum visit in the form of a Facebook game.

Other scholars focused on the role of motivation in shaping visitors' paths [47, 107], suggesting definitions such as researchers, browsers, searchers and followers [97], with the first two preferring to wander in the museum instead of following a suggested path. In order to provide a satisfying and effortless experience, a mobile guide should also take into account that people's attitudes can change throughout the visit. According to the literature, cruising behavior frequently occurs when fatigue overcomes attention, especially for first time visitors, while people familiar with a specific venue might assume a more selective visiting style [111].

Context evaluation and exploitation seem of crucial relevance. The effectiveness of all the aforementioned models and experiences depend heavily on how context is evaluated. If the digital medium does not "know" or "understand" by whom it is being used, that means contextual recognition is not achieved then the guide can not adapt to whom is using it.

2.1 Context relevance

The Cambridge dictionary defines context as "the situation within which something exists or happens, and that can explain it". In other words context is any information that can help understand a situation. It answers questions such as who, where, when, with whom, how, with what. Context can be personal, social or even environmental but this are all parts of the same unique concept that can be used to understand and give meaning to any particular action. Looking at somebody pressing against a wall with a finger might make no sense if we did not know that under his finger there is the light switch. The information regarding the button has given a context to the action of pressing the finger against the wall and has made this action meaningful.

In the same way contextual information could be used to situate visitors actions in a certain cognitive-spatial-temporal dimension in order to make sense of that action and the underlying plan that action is part of. If this plan is correctly inferred then the device knows how to continue the interaction with the user.

Situated Actions

Human actions are always situated in particular environmental, social and personal circumstances. The ways in which individuals try to control interaction are contingent and derived from the situated action that they represent [135].

Cultural venues offer many insights for reflections on situated interaction: visitors have heterogeneous needs, their behavior is not predictable and nobody declares what his plans are for the visit at the museum entrance. Most of the time their activities are "non-goal oriented" since they can be motivated just by curiosity or pleasure. They often do not know ahead of time, or with any specificity, what future state they desire to bring about [135]. This can be caused by the intrinsic motivations that might arise/change during the visit because of the museum "hooks". The final outcome of these fluctuations is that visitors will have to adjust frequently their goals and objectives during the visit. The mobile device accompanying the visitor has to take into account these changes. This way, it will be possible to infer any underlying plan that might be not clearly known to the visitor.

In her PhD dissertation "Plans and Situated Actions" [135], Suchman introduces the concept of "situated action" to underscore the fact that the course of actions depends upon the action's circumstances.

> "It is frequently only on acting in a present situation that its possible future states become clear. And we often do not know ahead of time, or at least not with any specificity, what future state we even desire to bring about; only after we encounter some state of affairs that we find to be desirable do we identify that state as the goal toward which our previous actions, in retrospect, were directed." [135]

The presence of an intelligent agent mediating our visit in the museum could ease the process of understanding or keeping track of the course of situated actions that are building the current plan. The role of this agent in maintaining the flow state is clear. But in order to "understand" how a visitor behaves, or put in simpler words, make sense of the course of actions, this system must have a model describing and categorizing users behaviors.

Having a model does not mean that users will behave all the time according to those categories. Their category could change during the visit as they progress in their course of situated actions, are attracted by other artworks in display or are just overcome by fatigue and start to lose attention and interest. Conceiving a general model that comprises every possible situation or scenario is not realistic, but still having a model that simplifies somehow the approach to the problem makes it easier to elaborate a "good" solution for the targeted problem.

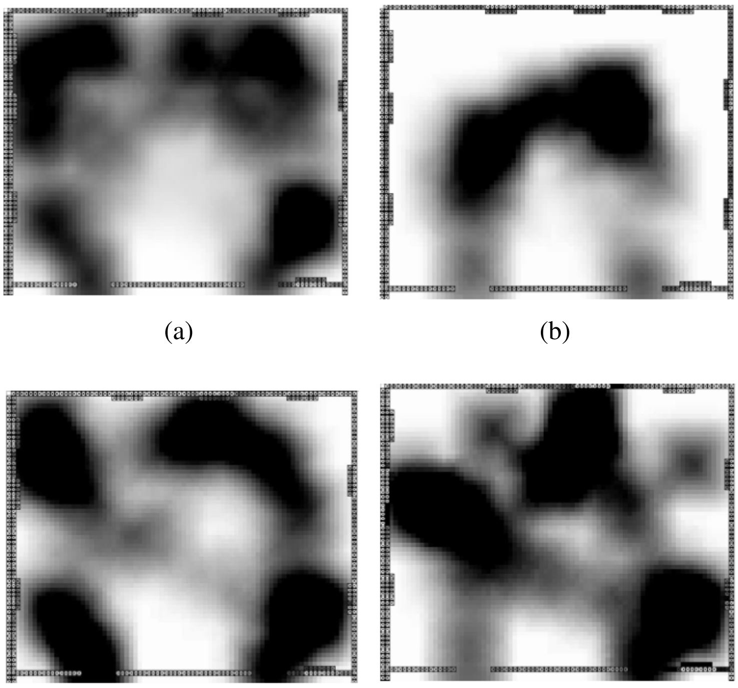
The ant, the fish, the grasshopper and the butterfly

A suitable and fascinating model was elaborated by ethnomethodologists Veron and Levasseur [143] in 1983. After having carried on systematic observations of visitors movements in the Louvre Museum for weeks with the purpose of understanding users behaviors and classifying them through a model. The resulting classification proposes four categories representing each a different visiting style:

- **Ant**, this kind of visitor behaves like an ant, meaning that he/she is very laborious and explores almost every cultural artifact in display in the museum exhibit.
- **Butterfly**, does not follow a specific path but is rather guided by the physical orientation of the exhibits and stops frequently to look for more information
- **Grasshopper**, seems to have a specific preference for some pre-selected exhibits and spends a lot of time observing them while tending to ignore the others. These visitors have clearly a plan that is prior to the museum visit
- **Fish**, most of the time moves around in the center of the room and usually avoids looking at exhibits' details. This kind of visitor is probably the one needing a particular help in order to create a course of situated interactions that will actually help him in the meaning making process

Of course, it could happen for a visitor to change his/her behavior during a long visit. In certain circumstances it is desirable that this happens. It is the case for example of "fish" visitors that might be a little lost at the beginning. But, as soon as the system understands who he is and how to properly stimulate him, the visitor starts to makes sense of the surroundings, thanks to our hypothetical guide, and profits from his visit.

A visual representation of these visiting styles is presented in figure 2.2. The Butterfly and Grasshopper visiting styles look a lot alike but it is still possible to separate the two categories by further analysis [29]. The ant and the fish on the other hand present very stereotypical behavior and the corresponding styles are very different from the other two.



(a) (b) (c) (d)

Figure 2.2: Visual representation of visiting styles: (a) Ant, (b) Fish, (c) Butterfly and (d) Grasshopper, images from [29]

2.2 Context

In the previous section we saw that in order to infer the visitor's state of flow and the visiting style we need to analyze his actions and contextualize them. By doing so we must take into consideration some basic information like physical location and time. This apparently basic knowledge makes it possible to situate this particular action in time and space. If this action is then correctly analyzed together with the others that preceded it then we obtain a course of actions that can provide relevant information regarding the visitor's state.

This means the mobile device has to "understand" the user's situation by analyzing his/her context. In order to achieve this, for the adaptive multimedia guide purposes, it must take into account where the visitor is, what is he doing, where is he, how long has his visit been and so on.

2.2.1 What is context?

In computer science context regards both the user and the application and a good definition is the one made by Dey and Abowd:

> "Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves" [39].

By collecting and properly interpreting context information, computer systems can become much more friendly, easier to use, effective in supporting people's goals and capable of improving the overall quality of life.

Contextuality is a relational property that holds between objects or activities. It is not something that can be determined a priori, and the major concern with it is not how to represent it. Instead, what is, or is not, context "is an emergent feature of the interaction, determined in the moment and in the doing" [43].

In order to analyze context we first must collect all the information that relates to it. This can refer to the following aspects:

- location, is one of the most obvious characteristics. It makes possible to distinguish between different artworks and offer interactions that evolve according to the course of the visit;
- time, it is another relevant property and can be used to relate actions and locations between them;
- execution state of the application, it's knowledge makes it possible to have execution flows to structure the experience;
- computational resources, this kind of information could be used to decide what interactions can happen with the current set of resources, which can change over time;
- network bandwidth, used for example in video streaming applications to decide the stream quality;
- user activity, it is somehow related to the application state but not fully intertwined. Some user actions might be plausible even in different states of the application;

- user intentions, can be inferred from his actions and if correctly anticipated could make the interaction feel more natural and immediate from the user's perspective
- user emotions, difficult to measure but in certain conditions it could be feasible. They can be used to change the songs in a play list to adapt to the user's mood;
- environmental information, such as temperature and humidity;
- every other information that can be sensed and that could be helpful within the scope of the current application.

Context-aware systems and applications are part of the ubiquitous computing wave that starting in the early 90's represented a revolution in computer science.

Ubiquitous computing

The term ubiquitous computing was coined by Mark Weiser in his 1991 paper "The Computer for the 21 Century" [149]. Weiser starts his paper with consideration about the "literacy technology", as he calls it. Writing is ubiquitous in our lives and it is present everywhere. Signs, billboards, graffiti altogether with books, magazines and journals are all based on this technology. Nevertheless it does not require an active attention as reading is embodied in us and we access that information without any fatigue. Weiser envisaged this new world were computing becomes part of everyday life and people do not need to realize or know that it is there.

> "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it"[149].

In order to support effectively a person, context aware applications should ideally be perceived as part of the natural background and not require specific attention.

When we check the email on our smartphone we do not normally think of the "cloud" services or the internet as being part of that interaction. But they still are. Our smartphone alone is useless, but when put in the right distributed computing scenario it becomes a very powerful computer because of all the complexity that is hidden behind the touchscreen.

Wearable systems have pushed this concept further on and now we have little computers that can be kept in our pockets, put on our wrists or necks and are continuously monitoring our actions for fitness or health purposes. When we use the washing machine we forget that there is a small computer inside it. And soon with advancement of the Internet of Things concept this little computer will be connected to the Internet and this enable a different set of interactions with this device. These computers become ubiquitous the moment we start using them unconsciously for everyday tasks.

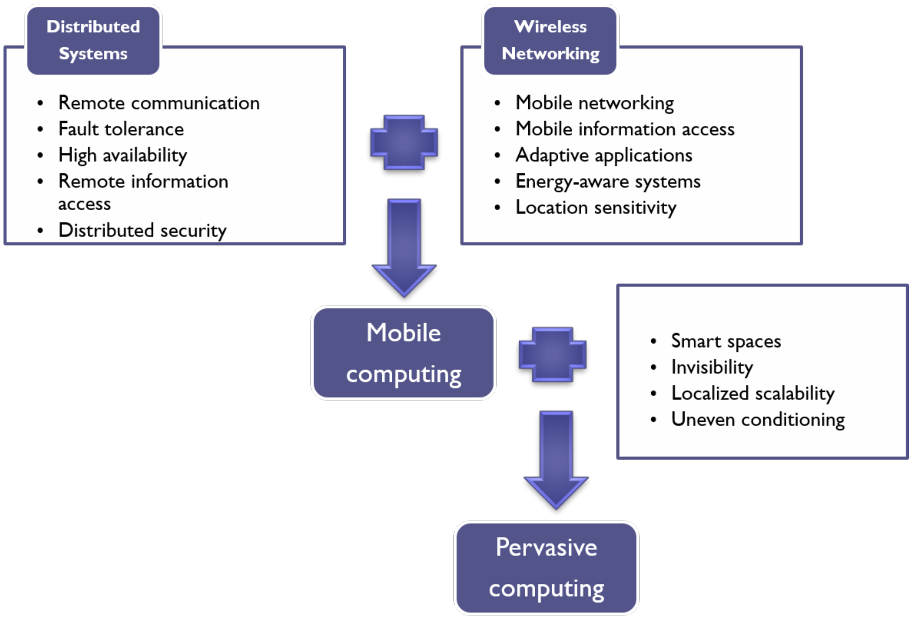


Figure 2.3: Domanis related to the Ubiquitous Computing paradigm.

The parallel with the smart adaptive multimedia guide is evident. A system composed of many sensors spread over the environment and a hand-held device that silently uses this distributed system to understand where you are and what you are doing. The museum becomes a smart space and this smartness is used to make the visitors experience more enjoyable and profitable.

A context-aware pervasive system can be viewed as having three basic functionalities: sensing, thinking and acting, interwoven by data transmission as shown in figure 2.4. After deciding what is context and which parts of it are interesting in a certain use case the process of exploiting this information consists of three steps:

- Sensing, in this step contextual characteristics are sensed/measured and the resulting data is forwarded to the next step
- Thinking, data coming from sensors is filtered and elaborated and decisions are made regarding the current identified situation

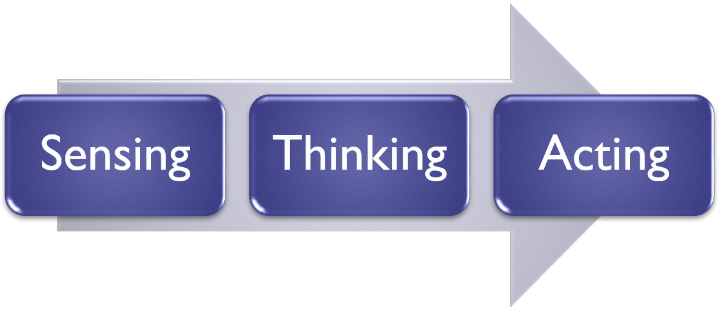


Figure 2.4: Context loop.

- Acting, the previously made decisions are translated into actions such as enabling certain interactions instead of others.

2.2.2 Sensing context

Sensors provide a means to acquire data or information about the physical world. A sensor can be any device, hardware or software, or their combination, that can be used to acquire context information. A thermometer is a sensor and it measures a physical quantity. A camera device is a sensor that captures the quantity of light emitted or reflected by objects but it can become another kind of sensor when it's images are processed through computer vision techniques in order to understand what the camera is pointing at. There are three main categories of data that can be sensed:

- Environment data : light, temperature sensors, humidity, air pressure, smoke detectors
- Biological signals : heart rate, skin resistance, muscle tension, blood pressure sensors
- User activity : motion, touch, audio, location and position, proximity, user interaction sensors

Context sensing seems kind of magic sometimes and the results are impressing. In the latest iteration of the Android Operating Systems a new feature was presented to the public, Now On Tap [1]. When you press the home button as in figure 2.5, the Android

[1]Google Now On tap : https://www.android.com/versions/marshmallow-6-0/#now-on-tap

OS processes your current screen, senses your context. After having collected enough information data is presumably sent to Google's data centers to be processed and the outcome results are presented to the user.

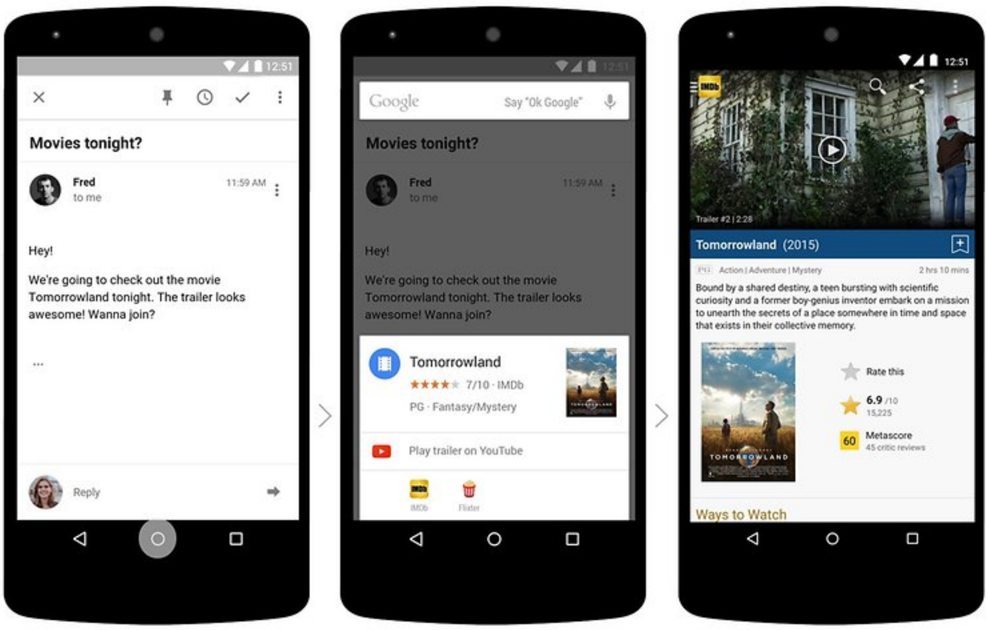


Figure 2.5: Google's "Now on Tap" in action.

Even lights can become sensors as it is the case for indoor positioning techniques based on visible light communications [2]. In this second scenario sensors are represented by LED lights that switch ON/OFF states so quickly that the human eye does not notice any change. This fast switching states are detected by the smartphone camera that then translates this states into information.

Sensors can be deployed in many ways. They can be worn on people or embedded in the environment in many forms. Wherever they are, power is a major concern. If they are battery operated, it must be recharged or replaced when needed. If they are powered from mains, power lines should be deployed (it becomes problematic outdoors).

[2]Philips led based indoor positioning http://www.ledsmagazine.com/articles/2015/05/philips-lighting-deploys-led-based-indoor-positioning-in-carrefour-hypermarket.html

2.2.3 Processing context

Sensed data must be collected and processed. Interpreting this data is not always a trivial task. It is when all we have to do is to turn on an LED because temperature has reached a trigger level. But it is far from trivial and easy in almost every other kind of interaction. Data processing could be carried in two possible ways:

- in a centralized fashion: data is collected in a single place (this requires taking data to this central node)
- using distributed algorithms (requires information exchange).

Either way communication protocols and some kind of networking infrastructure must be taken into account and must be properly designed.

2.3 Existing systems

Based on the thorough surveys of [45, 73, 77] I decided to focus my attention on a subset of guides that deal with the context-awareness problem. These applications propose some interesting solutions on how context could be harnessed with the purpose of making the museum experience a more enjoyable and profitable one. User's behavior is collected both in off-line and on-line fashion as the systems try to continuously adapt their contents and the proposed tours as the visitors advance on their museum exploration. The second part of this section analyses existing mobile museum games. Contex-aware games have been developed in the recent year with the double goal of making the visitors experience more appealing and, as a consequence, achieve a more effective learning that is pushed by visitors engagement through gamification techniques or storytelling approaches.

2.3.1 Mobile museum guides

A first notable example of an adaptive mobile museum guide is the HIPPIE prototype developed under the Hyper-Interaction within the Physical Space project (HIPS)[102]. It was implemented for an art collection near Bonn, Germany. The system was composed of web server running the application that could be accessed from anywhere. One of the definitions the authors give of HIPPIE is that of a nomadic system, meaning with that the the user can continue its experience even after the visit.

Museum visitors are equipped with a touch-screen enabled laptop. The available wireless connection of the laptop is used to retrieve data, while an infrared receiver is used for detecting user's location. As the visitor moves through the museum and accesses informations of interest on artworks in display, the underlying software builds a user profile for this particular visitor. The latter is then used to present the visitors with visual and audio cues when he passes nearby exhibits that might be of his interest. Content adaption is based on the location of the user (at home or in the museum), her interests (represented by common attributes identified in the visited museum exhibits) and preferences. The system can provide location capabilities through an infrared emitter placed over each exhibit while the orientation is determined through an electronic compass.

The authors reported that visitors with extensive interest and prior knowledge in art enjoyed and used the system more than visitors with only curiosity and lower knowledge used the system for short periods of time. This might depend on how this contents were prepared. In [118], we assessed how a different way of structuring and presenting the information leveraged higher levels of engagement by the visitor. For more details refer to 3.2.2.

With the Museum Wearable [131], Sparacino experimented a solution where a lightweight computer is carried by the user. The purpose of the computer is to offer an audiovisual augmentation of the environment by using an eyepiece display. A custom-built infrared network sensor allows the localization of the user. By continuously monitoring the user location and motion paths the system is able to build a user profile and produce contents accordingly. This experiment reveals the relevance of visitors movements for determining its visiting style, a concept pushed further by the designers of PEACH[133]. One of the prototypes of the PEACH project was tested in the Torre Aquila museum in Trento, Italy. 143 visitors participated in an experiment reported in [78]. They were given a mobile multimedia guide and their interactions with the system and the movements inside the museum were recorded. Data analysis of the visitor behaviors (time length of the visit, order of the visit, percentage of completeness amongst others) resulted in 4 different kinds of behaviors that the authors identified with Veron and Levasseurs' model [143]. Based on these findings the authors used these classification model to analyze the visit logs with the purpose of predicting the visitors behavior. Their findings are shown in figure 2.6.

The ANT, BUTTERFLY and GRASSHOPPER visiting styles are identified after almost 10% of the visit. The FISH visiting style, on the other hand, is correctly identified after half of the visit. Other analysis on the effectiveness of the prediction revealed that

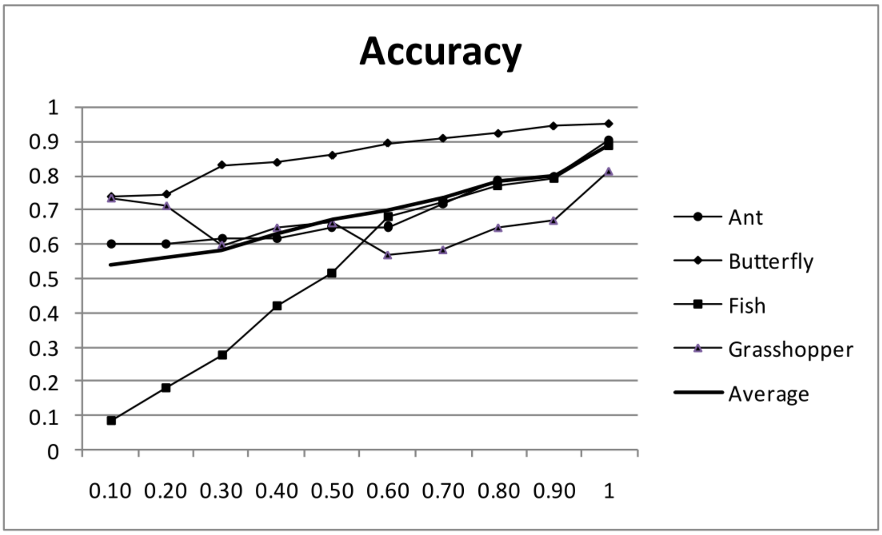


Figure 2.6: Accuracy of predicting museum visitors' type based on their behavior during the visit. Image from [78].

the predictions were not so successful, especially for the FISH category. Their conclusion is that more data about users behavior is needed. They also suggest that the same analysis applied to visits of larger museums could leverage the longer time of the visit, and as a consequence a greater amount of behavioral information, to more effectively predict the visiting styles.

Another interesting attempt at using contextual information to offer a better experience is the CHIP[117] demonstrator for supporting visits of the Rijksmuseum in Amsterdam, Netherlands. CHIP is a web-based application that can be accessed from any browser. Users profiles have been previously built before the visit through the tour wizard tool. During the visit these tours are proposed to the visitor and they are adapted after the user interacts with the system and tries to access artworks not available in the precomputed tour. User interaction is required to trigger the tour update process. Author findings suggest that in this case, in contrast with the HIPPIE project, novice visitors were the ones who obtained more benefits from using their system.

2.3.2 Mobile museum games

The use of context-aware mobile games matching educational and entertainment goals has been experimented in a variety of museum contexts in recent years. Experiments have been conducted on the use of location-based mobile games to enhance young visitors' experiences, as the intrinsic appeal of the media for digital natives and the active role demanded to the players while moving through the physical space usually promote participants' satisfaction [18, 92, 124, 137, 147].

With regard to context-aware applications including augmented reality features, the research questions that have been usually investigated mainly concern the efficacy of these applications in terms of :

- communicating cultural content,
- fostering a purposeful interaction with the objects on display and
- encouraging the social sharing of the experience [18, 92, 137]

If the use of dedicated mobile applications to explore museums may definitely attract visitors' attention and represent an element of curiosity in itself, a concern raised by practitioners and scholars is that this use could also actually distract users from the real objects, the physical environment and social exchange [89, 121], ultimately limiting the learning potential of the experience. Additional elements of discussion are the provision of challenges that balance the skills of users [20] and the invention of tasks and stories that are able not only to hook but also to maintain visitors' attention: these issues are particularly relevant since they may influence visitors' level of engagement and their meaning-making process.

If the acquisition of knowledge is usually regarded as one of the most important outcomes of mobile gaming in museums, the use of mobile tools in the museum context can be beneficial for other reasons, too. For instance, children aged 6-9 interacting with a mobile game at the British Museum manifested as unintended learning outcomes stemming from the mobile activity the improvement of kinesthetic skills: children improved their coordination with regard to the scanning of tags while progressing in the game and repeating the gestures needed to activate the tags [92]. Another important outcome that has been underlined as particularly important by authors is the facilitation of social interaction. With regard to this aspect, the analysis conducted at the Asian Civilizations Museum pointed out that a mobile game developed to convey cultural content on Chinese terracotta warriors was effective in fostering a purposeful social interaction between parents and children [137]; other examples have also stressed the potential of mobile tools in fostering peer-to-peer interaction [147], whereas the shared use of a 7 inch tablet among a group of teenagers was found inappropriate, instead [92], confirming that external conditions and the social composition of groups may influence the effectiveness of the m-learning experience.

The types of activities and approaches proposed through the applications may influence the experience, too: narrative approaches aim at emotionally engaging visitors with the story that is being told [88], whereas more constructivist and task-based experiences usually encourage self-directed exploratory behaviors. Given that both the approaches are appreciated, the selection of the method to be followed should be tailored by developers according to the goals and the learning theories at the base of the mobile experience.

Enjoyment and engagement experienced by participants are highly valued as well by an educational point of view: in fact, they are considered not only as conditions facilitating learning but as learning outcomes in themselves, together with the development of knowledge and understanding, the improvement of skills, and the changes in values and attitudes [67]. A recent survey has pointed out that among the range of digital games developed to foster awareness on cultural heritage, the most common approach is represented by quizzes and puzzles [98], whereas the "adventure" or "action" genres are still a minority. The extensive use of riddles [20, 57] is well justified in light of task-based learning, a pedagogical theory that stresses the importance of concrete, focused activities to develop knowledge and skills [13, 151]. Administering isolated tasks may be a successful option because it also allows easy inclusion of ad hoc joining and leaving mechanisms that enable the users to play with the application as they like. However, the need to experiment with game mechanics that may encourage players' engagement throughout the whole visit and thus expose them to a larger variety of learning stimuli is widely advocated [31, 98] .

Apart from game mechanics, another way to capture visitors' attention and communicate cultural content is represented by digital storytelling [21, 88, 100]. The interactivity allowed by digital technologies has pushed forward the narrative potential of storytelling, giving visitors the chance to enrich their experience with multimedia contents and customize the stories according to their own interests. The increase in interactivity has particularly favoured nonlinear storytelling—a particular approach where events are not strictly presented in chronological order but depend on other criteria [36, 152], such as the position of the user in a given environment. The relationship between interactivity and digital storytelling has been further explored by Sharples et al. [130], who have borrowed from the gaming theory [162] the concept of "explicit interactivity" and applied it to mobile digital storytelling: through a combination of human-computer interactions and physical movements around the space, visitors have the opportunity to connect with interactive objects and affect the content of the story as it is being delivered. Then, various types of interactive digital storytelling have been identified by authors:

- tree-branching structure, where the user is presented with the possibility to choose among several possible situations;
- braided multilinear experience, where a core narrative branches into a number of plot directions, which then converge and reintegrate with the core; and
- rhizome, where stories of many visitors are interwoven and narrations depend on paths taken by other people or on the frequency locations have been visited [130].

As underlined by Ioannidis et al. [69], the main challenges and issues that currently lie in the introduction of a digital storytelling approach in a museum setting concern the three separate aspects that are involved: the museum topology, the museum objects, and the story concepts. As a consequence, the different components of mobile digital storytelling tools need to be carefully balanced to match personalization and engagement with the achievement of behavioural and learning objectives that go beyond pure entertainment [14]. Whereas at this stage of research a wide number of mobile applications aiming at enhancing the visitor experience has been presented, there is still a relative lack of publications thoroughly analysing how they can create particular contexts of visits, ultimately influencing visitors' behaviour and learning. For instance, the work of Chang et al. [23] pointed out that visitors using a mobile application featuring augmented reality functionalities registered a better learning performance if compared to visitors who carried out the tour using an audio guide or without any support. Lanir et al. [83] have compared the behaviours and circulation paths of the visitors who used a multimedia guide to the patterns registered for people visiting the museum without any support instead, finding that visitors using a mobile guide stayed in the museum longer and spent more time in front of the exhibits when they could get information from the guide.

The next Chapter is dedicated to MusA, a set of mobile applications designed, developed and evaluated at the Palazzo Madama museum in Turin Italy with the purpose of offering more enjoyable and profitable experiences to the museum visitors.

Chapter 3

MusA experience

This chapter was based on and contains extracts from the following papers that I coauthored [118, 119, 120, 153]. As stated in the introduction of this thesis I participated in the design, development and assessment the following mobile guides, two of which in the form of location based games.

In this chapter I present Museum Assistant (MusA), a general framework for the development of multimedia interactive guides for mobile devices. Its main feature is a vision-based indoor positioning system that allows the provision of several location based services, from way-finding to the contextualized communication of cultural contents, aimed at providing a meaningful exploration of exhibits according to visitors' personal interest and curiosity.

Palazzo Madama-Museo Civico d'Arte Antica is a UNESCO-listed World Heritage site and ancient art museum located in Turin, Italy. Especially renowned for its baroque facade, the building still preserves beautiful 18th-century frescoes and an extensive collection of decorative and fine arts displayed on four floors, on a surface of more than 4,000 square meters. Even though the baroque era played a major role in the definition of the history and the art of the building, the interpretative concept of the site primarily focuses on the artworks on display: as a result, the political role played at that time by the royal Savoy family, together with the stories of the people who inhabited the palace, are not perceivable during traditional visits.

The museum's collections are organized in four categories over the four floors of the building:

- medieval stoneworks (moat level)

- Gothic and Renaissance masterpieces (ground floor)
- Baroque art (first floor)
- decorative art objects, such as ceramics, textiles, glassware and ivories (last floor).

,

This heterogeneity, combined with the extension of the venue over 4,000 m^2 , makes Palazzo Madama a particularly multilayered and complex cultural context: as a result, visitors have frequently reported difficulties orientating themselves inside the building. Additionally, previous studies have pointed out that only a minority of visitors actually follows the thematic and chronological paths designed by curators, showing critical issues with both physical and cognitive orientation [19].

Based on these observations, the authors deemed Palazzo Madama as being particularly suited for experimenting with the functionalities of MusA in a real and challenging scenario. To this end, three different applications were developed:

- Step by Step, a mobile museum guide addressed to an adult audience
- Gossip at Palace, a serious game targeting young adults
- Intrigue at the museum, a location-based game specifically designed for children.

The applications were deployed and thoroughly experimented in order to analyze the user experience and the visitors' appreciation of the applications.

In this section I will describe the various features that are available in MusA to build interactive multimedia mobile guides for museum and cultural sites in general. As I stated in the Introduction, MusA is a general framework that focuses on two main issues curators and exhibit designers have to face:

- supporting mobile users with information of interest related to the works of art on display or the surrounding environment and
- helping them to follow their visit path inside the venue.

Both these problems are addressed in our solution through the delivery of location based services, which rely on the accurate identification of the indoor location of the visitor by means of a vision-based positioning system. In the following subsections we describe the key features of MusA:

- indoor positioning;
- indoor navigation;
- the management of rich contents related to the cultural items of the exhibits;
- the design and management of compelling thematic paths;
- the integration of social networking features.

3.1 Indoor positioning with custom markers

Computing metric information from 2D images requires a fundamental step known as camera calibration. The aim of this process is to compute, for a given camera, both its extrinsic parameters (location and orientation of the camera in the world reference system) and intrinsic parameters (describing the relationship between pixel coordinates and camera coordinates). Camera calibration requires knowledge of the correspondences between a set of known 3D points and their projection on the image plane. These correspondences can be often obtained from known calibration objects, exploiting a set of 3D reference points [51, 138], images of planar patterns under different perspectives [134, 158] or sets of collinear points [159]. As an alternative, self-calibration techniques, relying only on the point correspondences between different images, can be used [95].

In a marker-based localization system, like the one used in our work, camera calibration aims at computing the camera pose from a single planar target. This process is often divided into two steps. First, the position and orientation of the sensing device, relative to the local reference system of a visual marker, are computed from the identification of the relevant marker features. Then, the absolute position of the device can be computed by knowing the feature positions in a reference frame.

The main problem to face in this case is that camera pose can be computed from at least four co-planar and not collinear points if the intrinsic camera parameters are known [72, 91, 125], while robust and full calibration from a single image still remains a challenge. Several algorithms have been proposed in the literature to solve this problem, exploiting either vanishing points [58, 103], vanishing lines [144], conics [24, 27] or the image of the Absolute Conic [134], usually making some assumptions on the intrinsic parameters (e.g., zero skew or known principal point) to reduce the complexity of the problem.

Given the possible application scenario of a MusA based mobile guide and the fact that it can be potentially run on any off-the-shelf mobile phone, we took into consideration the following points in the development of our pose estimation approach:

the positioning algorithm should be as light as possible in order to be executed in real-time, even on devices offering limited computational power; hence, for these devices, approaches requiring the optimization of non-linear objective functions with complex and iterative algorithms (e.g., [25, 125]) are not the best-suited;

a lightweight algorithm, requiring a low amount of energy for its execution, helps reduce the device battery consumption, which is a vital parameter for any application aimed at supporting the visitor for a medium to long time span;

any approach requiring one to know in advance the intrinsic camera parameters (e.g., [25, 123, 125]) is again unsuitable, since these parameters vary from camera to camera, thus requiring a database of camera parameter sets, periodically updated to consider new devices;

in indoor positioning and navigation, the environment is usually represented by 2D maps and, thus, the localization data can be reasonably expressed with only three degrees of freedom [99]; another thing to consider is that, in most scenarios, a reliable indication of the user orientation inside a building is required to provide useful navigation information, while we can be satisfied with a less precise estimate of the device position, or even considered it as co-located with the detected marker.

With this in mind, we designed a novel visual marker, whose peculiar shape and geometric properties allowed to develop an approximate algorithm for the computation of the camera pose with the following characteristics:

it does not require prior knowledge of the intrinsic parameters of the camera; it is not iterative, guaranteeing a fixed execution time; it is computationally light (i.e., it can be executed in real-time on any mobile device), while ensuring, at the same time, a sufficient level of robustness and reliability for its expected use.

3.1.1 The structure of our marker

We designed our marker taking into consideration the following constraints:

- providing the minimal amount of information required to solve the so called Perspective-n-Point (PnP) camera pose determination [52];

- guaranteeing some geometric properties that help improving the accuracy and robustness of the camera pose estimation and;
- encode an ID into the marker shape.

Our star-shaped marker, sketched in figure 3.1, is planar and it is obtained by combining, on a white background, two black squares with the same side, the same center and mutually rotated by 45 degrees. The use of black and white colors for the marker guarantees an easier segmentation and feature extraction. The marker silhouette always contains, even under perspective distortion, a sequence of 16 alternate concave and convex corners. One of the triangles of the star includes a white circle, which allows one: (i) to define a local reference system aligned with the marker; (ii) to univocally identify the projections of the marker corners on the image plane.

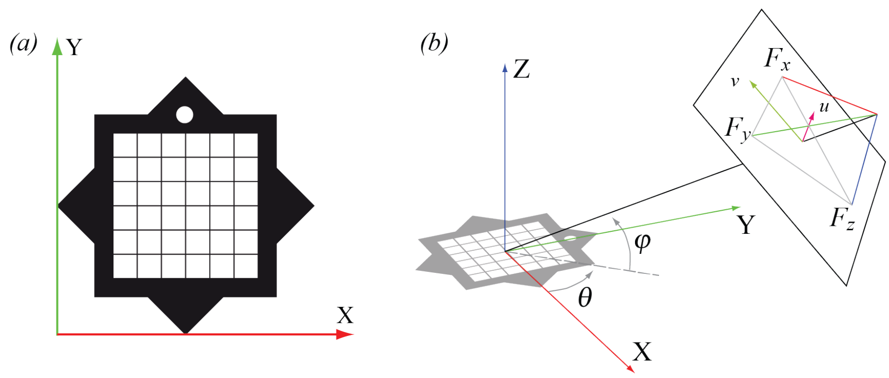


Figure 3.1: The marker used in the Step by Step applications (a) and the relative position of camera and marker (b).

The inner part of the symbol contains the data area, divided into a regular grid of N^2 blocks each of which represents a data bit, where the extra information associated to the marker is stored.

3.1.2 Marker detection

The marker detection takes into account possible variations of illumination from frame to frame using an adaptive threshold to binarize the camera frame. In details, if a marker was detected in the previous frame, the threshold is the average of the highest and lowest intensities of its pixels, otherwise a random value is picked until a new marker is detected. After binarization, all the connected components bigger than a predefined area are treated as candidates and their contour is reduced to a set of vertices with the Douglas-Peucker algorithm [42]. A candidate is identified as a marker if its contour contains a sequence of exactly 16 alternate concave and convex corners and the characterizing white circle is found. This peculiar sequence of corners allows the use of larger thresholds in the Douglas-Puecker algorithm, making the corner detection more robust when compared with other convex markers (e.g., [99, 25]).

The precision of the corner positions is finally improved considering that each of them lies at the intersection of two of the straight lines passing through the sides of the marker squares. These lines are computed, with the Total Least Square method [2], as the lines best fitting the contour points between the four corners they traverse.

Our libraries can compute the full 3D position and orientation of the camera relative to the marker, with an approach similar to the ones described in the literature, by exploiting marker's geometrical features and how this is done will be further explained in 4.3.4.

3.2 Step by step : the museum guide

Figure 3.2: Palazzo Madama, aerial view

The implementation and use of MusA in a museum context has been recently tested at Palazzo Madama—Museo Civico d'Arte Antica, a historic building and UNESCO World Heritage Site located in the city center of Turin, Italy (figures 3.2 and 3.3). Palazzo Madama is especially renowned for its baroque style, but it also hosts the City Museum of Ancient Art (Museo Civico d'Arte Antica), which counts with an extensive collection of decorative and fine arts covering a span time of over eighteen centuries.

Figure 3.3: Indoor view of Palazzo Madama

Step by step is a mobile guide aimed at guiding visitors through the museum collection. Relying on MusA functionalities, three thematic paths were developed by exhibit designers:

- "Great Treasures", devised for helping visitors with tight time constraints to discover the museum masterpieces
- "Discover the unusual", a selection of the museum's works of art that present uncommon and usually unnoticed characteristics
- "Decorative techniques", focused on the materials and the techniques mastered by artists over several centuries

These paths were developed in order to cater to visitors' interests and visiting agendas. Additionally, considering that visitors have different visiting styles and may prefer not to be guided in the museum, users are also able to build their own personalized visiting path through the "Wander and learn" tool, which let them freely select the rooms and works of art to be explored. To provide maximal flexibility, users are allowed to switch the current visit theme at their will.

The users can then be guided at any moment to their next destination (figure 3.4 a) activating the navigation function and pointing with the tablet at a MusA marker in their surroundings (figure 3.4 b). When the tag is recognized by the system, the navigation data are presented to the user on the tablet display. To make this information as clear and readily understandable as possible, route communication integrates, as suggested in Section 2.2, different elements: a 3D map, rotated according to the user orientation, and an arrow showing in AR on the camera image the current walking direction. The whole path is described on the map and the user can control an interactive animation showing the detailed instructions to reach the destination (figure 3.4 c,d).

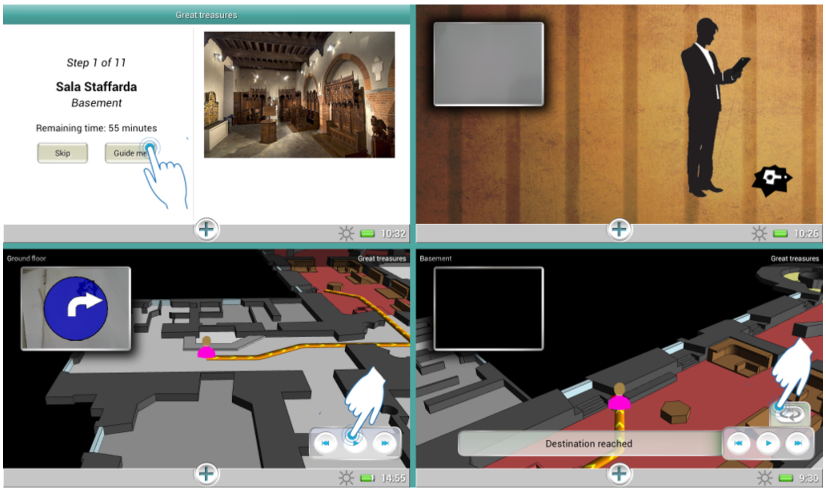


Figure 3.4: Screenshots of the application interface showing a step of the tour (a), the marker aiming menu (b), the 3D map and the path animation (c, d).

When the desired destination is reached, the user can activate the related contents by pointing the tablet to the marker associated to that item or, alternatively, clicking a button in the user interface. The layered contents are then fetched from the DB and displayed on screen according to their structure.

Visitors can access contents related to the environment and works of art on display also through hotspots embedded in interactive 360° panoramic images (figure 3.5 a,b). The rationale of integrating this feature into the guide is that the panoramic images allow a seamless shift between the image displayed and the surrounding environment, facilitating the interaction with the elements it contains [22].

Panoramic images also allow a reduction of the number of tags installed in the museum rooms. Furthermore, they offer visitors the possibility to display, and eventually access, other items present in the same room but not included in the thematic path chosen (figure 3.5 c,d), which can possibly foster visitors' interest into alternative paths in the museum collection.

The whole application can be customized by users, selecting the display language, requesting accessible routes or modifying the interface setup, e.g., to display contents designed for dyslexic users (figure 3.6).

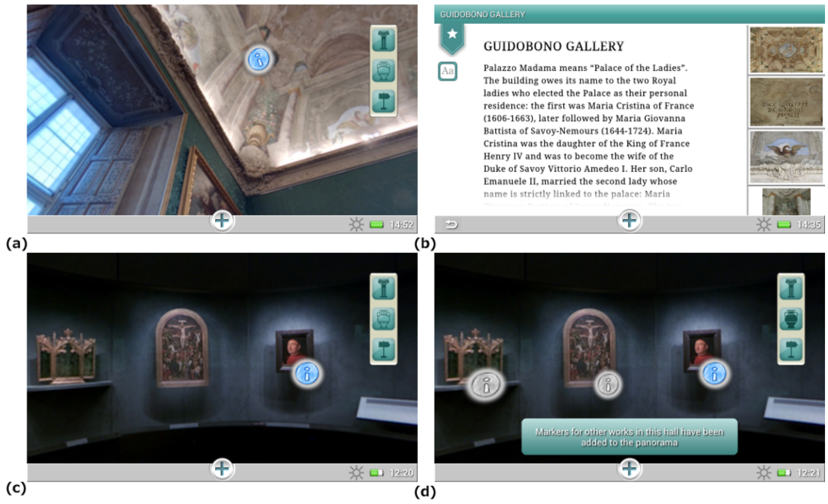


Figure 3.5: An interactive hotspot (a) and its related content (b); a panoramic image showing the path hotspots, in blue (c), as well as those included into alternative paths, in gray (d).

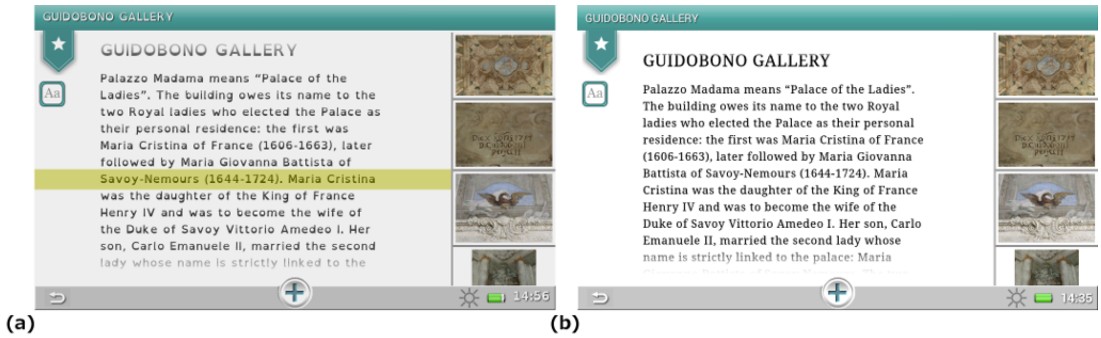


Figure 3.6: A screenshot of the interface for dyslexic users (b), which, compared to the version for non-dyslexic users (a), shows the usage of the OpenDyslexic font, a lowered contrast in the interface and the possibility to highlight the current reading line, helping users to focus on the text.

3.2.1 Step by step Evaluation: Results and Discussion

Volunteers were recruited at the museum ticket office, asking visitors to freely use the application and participate in the test. Each user was then provided with a 7 inch tablet to run Step by Step. In order to conduct the evaluation under realistic conditions, we preferred not to ask visitors to perform specific tasks, but rather to use the application according to their curiosity and interests. We gave some general information on the application, without explaining in details all its functionalities and let participants familiarize themselves with the use of the tablet through a sequence of introductory screens. Pre- and post-visit questionnaires were collected, followed by semi-structured interviews addressed to a subset of users. The panel was composed of 171 volunteers, 57% males and 43% females. The majority of participants were first-time visitors (75%). Visitors spanned different age groups: 36–50 (28%), 27–35 (26%), 18–26 (22%) and 51–65 (15%); participants younger than 18 years were only 5%, since they were invited to use Intrigue at the museum.

The pre-visit questionnaire mainly aimed at investigating the mobile user factor by collecting socio-demographic data, visitors' expectations and information about their level of confidence with mobile devices. As for the approach to technology, most of respondents (70%) declared to own a tablet or a smartphone, 25% of them perceived her/his level of confidence with these devices as "excellent", 40% as "good", 23% as "average" and only 5% as "low". Other results pointed out that most users decided to use the application attracted by new ways of exploring cultural heritage sites, desiring to get a better understanding of the museum exhibits. Interestingly, the possibility to support the navigation inside the museum, even if described as one of the application features, was scarcely mentioned among the expectations reported by volunteers.

Post-Visit Questionnaires

Post-visit questionnaires aimed at investigating the usability of the application, with specific regard to the ease of use, usefulness and satisfaction dimensions mentioned by the literature [7]. The questionnaire stimulated volunteers to express their level of agreement with a set of statements, using a 10-point Likert scale, or to make choices between options. Results are summarized in figure 3.7 which report the most relevant questions related to the three dimensions of our usability framework, their average ratings and a vertical line indicating their standard deviation. Most of the answers were found to be consistent (standard deviation in the range [1.55, 2.17]).

The overall degree of satisfaction manifested by volunteers towards Step by Step was positive, with an average rating of 7.51 (S12). Among the functionalities enabling visitors to access and interpret information, 360° photos were the most appreciated feature (8.15, S1), most likely for their intuitive nature. Other multimedia features such as photo-galleries (S2) and texts (S5) were rated 7.76 and 7.06, respectively, with texts acknowledged as easily readable (8.42, S7).

The lower rating of textual contents might be explained taking into consideration that they were not specifically tailored for the mobile guide. Given the limited number of

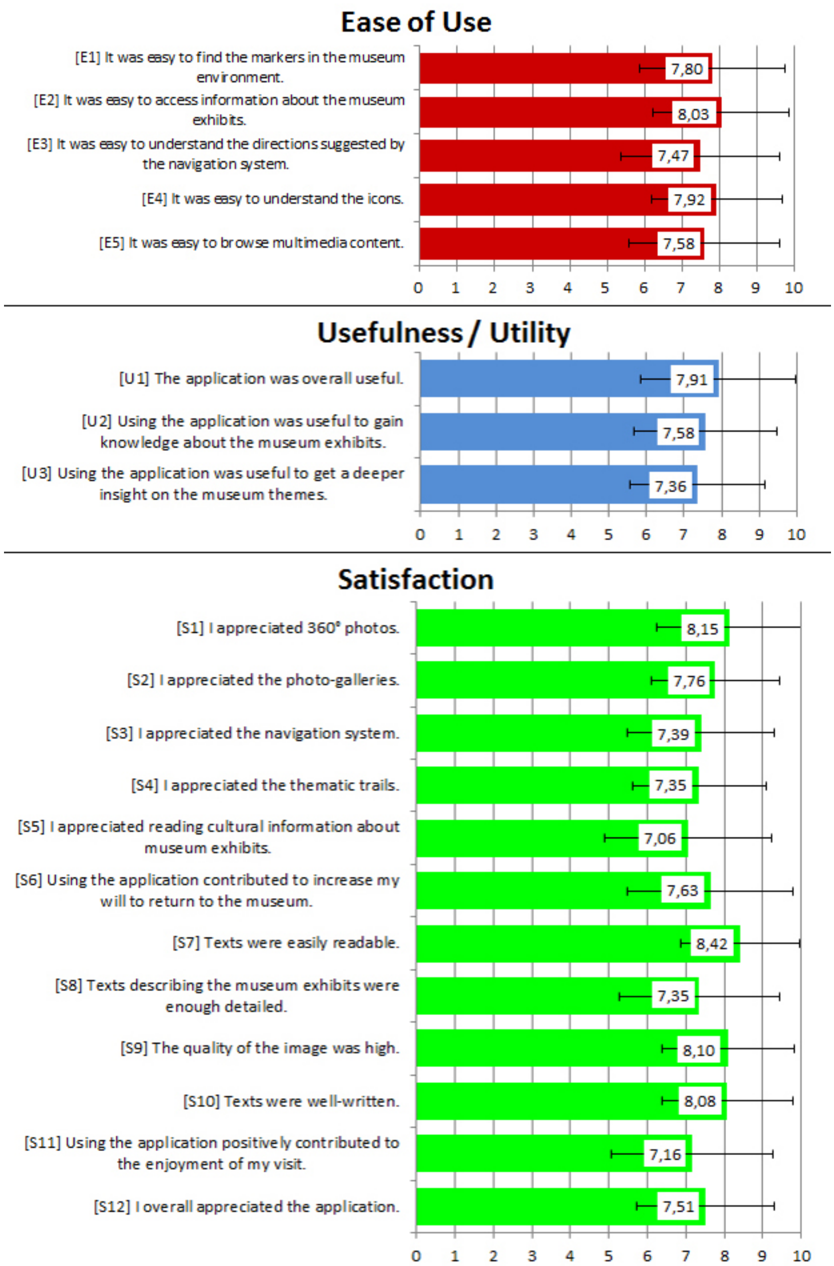


Figure 3.7: Post-visit questionnaires.

museum staff dedicated to the project, textual contents almost replicated those formerly elaborated for a printed guidebook and were not adapted to the device: for instance, they were definitely longer than the 600 characters that empirical studies underline as the limit to be fully read on a mobile device ([56]). Moreover, despite their verbosity and their perceived high quality (8.08, S10), some visitors did not find them detailed enough (7.35, S8). These results suggest that a better adaptation of the texts to the physical characteristics of the devices, the target audience and the context of use is sorely required.

The availability of different thematic trails (S4) was rated quite positively (7.35), suggesting that visitors generally appreciated the idea of potentially exploring the museum through a variety of perspectives, if so desired. Despite that, 76% of volunteers actually chose the free exploration tour. This suggests that the proposed themes were not fully matching visitors' motivations and interests and a better elaboration of trails is required to make this feature more appealing for the audience. As for the usefulness dimension, users agreed that the application was useful overall (U1, 7.91), facilitating to a certain degree the acquisition of a better knowledge (U2, 7.58) and a deeper insight (U3, 7.36) on the history of the palace and the works of art on display.

Indoor positioning and navigation (S3) were overall appreciated, receiving an average score of 7.39. Additionally, the analysis of the ease of use dimension pointed out that participants found the navigation process quite easy to follow (E3, 7.47) and the markers easily recognizable inside the environment (E1, 7.80). While indoor positioning and navigation still represent for visitors unexpected features for a museum context, as shown by the pre-visit questionnaires, our findings suggest that people generally appreciate these services once exposed to them.

Further statistical analyses were performed to better understand to what extent the technological, user and environmental factors influenced some of the usability dimensions investigated. More specifically, the analysis aimed at answering the following research questions:

- *Is the volunteers' satisfaction correlated to their familiarity with mobile devices?* Cross-tabulations (Pearson χ^2 test: 2.09, $p = 0.352$) pointed out that owning tablets or smartphones was not correlated to the degree of appreciation manifested by participants (S12, ratings above 7). This shows that, despite some limits highlighted by the evaluation, the interface of Step by Step was rather intuitive.

- *Is the acquisition of new knowledge correlated to the enjoyment of the visit?* (U2, S11) The correlation was found significant ($r = 0.643$; $p < 0.001$), suggesting that mobile guide contents may play a relevant role on visitors' enjoyment.

- *Is an enjoyable mobile experience correlated to visitors' will to return to the museum?* Our results ($r = 0.733$; $p < 0.001$) suggests that when the use of the mobile guide contributed to the enjoyment of the visit (S11), this also affected visitors' desire to return and visit the museum again (S6). These results seem particularly relevant both in terms of learning and marketing.

Finally, cross-tabulations highlighted a statistically significant relationship between the degree of satisfaction towards the use of the mobile guide (S12, ratings above 7) and the willingness to pay for the service (Pearson χ^2 test: 152.43, $p < 0.001$). Interestingly, of the 75 participants who were not keen on paying for the use of the tablet, 63 answered negatively since they did not want to have any additional cost on the ticket (10 euros) and not because they perceived the mobile guide as poor or useless. These results seem particularly valuable in terms of marketing and should be taken into account when thinking about integrating mobile services into a museum context.

Semi-Structured Interviews

A subset of 35 visitors was invited to participate to a semi-structured interview after the use of Step by Step to further investigate the usability dimensions, and to gain better insights into other aspects of the application use (table 3.1).

Overall, the majority of respondents (31) actively used the guide throughout the visit. However, (question IA5) 25 out of 35 people regularly combined the use of the tablet with the traditional habit of relying on informative tools such as panels, labels and touch screens. Considering that only four people had previous experiences with mobile museum guides (question IA6), it can be inferred that the mobile guide was perceived as a novelty and that people had to adapt to this new visiting approach.

As for the contents, 26 people stated that using the mobile guide was useful to get a deeper knowledge of the palace and of the museum collections (IU2). However, only 29 users regularly read the texts about the works of art on display (IA1), and only 18 visitors regularly explored the photo-galleries or the other additional contents. Interviews made evident that the interface was not clearly pointing out the availability of such materials, thus highlighting an element to be improved.

Twenty-two visitors used (IA3) and found useful (IU1) the indoor navigation system. Other participants preferred to wander throughout the museum by themselves, asking for directions to museum assistants or looking at maps in paper format, if needed. Again, this behavior was mostly explained mentioning traditional visiting habits. Some users found difficult to understand their position on the digital map (IE1) or the directions to be

Table 3.1: Outline of the semi-structured interviews

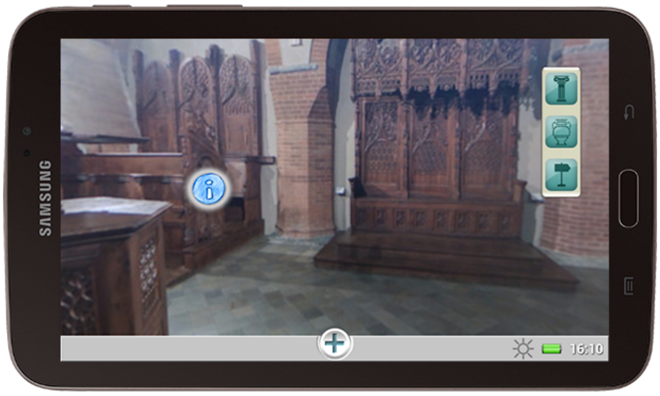
Ease of use
(IE1) Was it easy to understand your position on the digital map?
(IE2) Was it easy to understand the direction to be taken to reach your next destination?
Usefulness
(IU1) Was using the navigation system useful to reach your desired destinations?
(IU2) Was using the mobile guide useful to get a deeper knowledge and understanding of the history of the palace and the works of art on display?
(IU3) Was using the mobile guide useful to better manage the time allocated to your visit?
Satisfaction
(IS1) Was it pleasant to use the mobile guide?
(IS2) Would you recommend the use of Step by Step to your friends?
(IS3) How did you feel when using the mobile guide?
Additional Questions
(IA1) Did you read the texts describing the works of art on display and the rooms of the palace?
(IA2) Did you use the photo-galleries, when available?
(IA3) Did you use the navigation system?
(IA4) To what extent have you used the mobile guide during your visit?
(IA5) Did you refer to informative tools such as panels, labels and touch screens during your visit?
(IA6) Had you already used a mobile guide in a museum context before today?

taken (IE2). These problems are related, as previously commented, to the issue of map readability and route communication, which should still be improved.

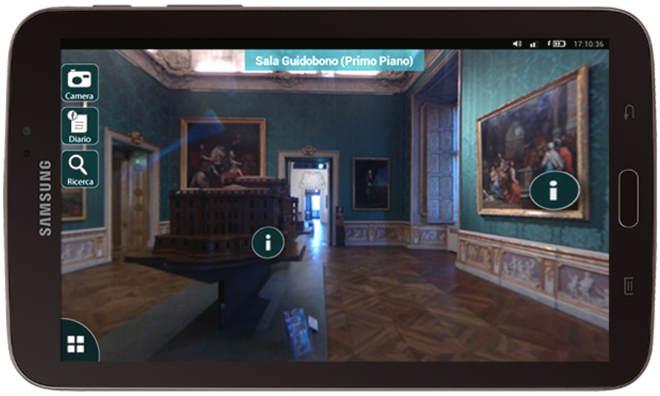
Concerning the satisfaction dimension, 30 participants found the application pleasant to use (IS1) and would recommend it to a friend (IS2), describing themselves when using the app as "interested", "focused" and "curious" (IS3). People who did not enjoy the use of Step by Step defined themselves as being "distracted", since recalling the operating principles of the system was difficult and reading long texts was negatively affecting enjoyment.

Finally, answers about the usefulness of the guide for the management of the visiting time (IU3) highlighted two different patterns: people who followed the guided tours used the guide effectively as a time manager, while, on the other hand, people who selected the free tour generally pointed out that accessing rich multimedia content induced them to explore in more depth the collection, satisfying their interests and curiosity, thus staying in the museum longer than expected.

3.2.2 Redesign of the user interface



(a) "Step by Step": augmented 360° photo and menu



(b) "Step by Step 2.0": augmented 360° photo and menu

Figure 3.8: Comparison of the 360° panoramic modes.

"Step by Step 2.0" aims at improving visitors' museum experience, by providing an easy to use digital tool that can go along the user throughout her visit, with a set of functionalities meant to support her meaning-making process. With this goal, the application was redesigned from different points of view: the interface was freshened and the number of functionalities reduced; the information on the artworks was completely restructured; and the navigation functionality was simplified.

First of all, we simplified the interaction model, in order to make the user complete her task without being overwhelmed by the interface. As pointed out by the Hick's law [85] (i.e. the time it takes to make a decision increases proportionally to the number and complexity of choices), the user's decisional process was facilitated firstly acting on the menu. The menu of the previous version of the application was considered hard to find as it was not always visible (Fig. 3.8a): some functionalities were directly accessible with the controls on the right, while others were shown when tapping on the "+" icon placed on the bottom of the display. In "Step by Step 2.0", the main menu functionalities were made always visible on the left side of the augmented 360° photo (Fig. 3.8b), while minor functionalities were made accessible through a toggle menu with collapsible items located on the bottom left side of the screen. Icons were moved from the right side to the left to increase accessibility, as stated in [96].

(a) "Step by Step": content presentation

(b) "Step by Step 2.0": content presentation

Figure 3.9: Different approaches for content presentation.

One of the major functionality of a multimedia mobile guide is to provide visitors information on the artworks that surround her or on the room she is in. In the first version of the application, when tapping on a hotspot, the description of the artwork was shown to the user in form of text and photo-galleries (Fig. 3.9a). The evaluation pointed out that the textual descriptions were considered reliable and well written, but definitely too long. Moreover, photo galleries with details and contextual images were not easily noticed by users and consequently not commonly browsed. These considerations drove us to completely rethink the contents to be provided to the user, moving from a mere replication of texts elaborated for a printed guidebook to a presentation of the cultural material specifically thought for a mobile context of use. Long texts were reformulated, simplified, and subdivided into small paragraphs that were shown in combination with explanatory images (Fig. 3.9b). This process was undergone also in consideration of the intended target of the application, i.e. common people lacking a deep and specialistic background in art history. The re-writing of the texts allowed to insert anecdotes that could foster visitors' empathy and emotional engagement; the extensive use of images and the subdivision of the contents into "slides" aimed at driving users' attention and make the information easy to scan.

Another major improvement consisted in improving the direct interaction with the multimedia guide. In the first version of "Step by Step", the main features of the guide were shown by a video tutorial, that was played as the application started. Interviews pointed out that this was confusing: in fact, some people did not notice it was a video and tried to interact with the interface in vain during the video playback. Moreover, users frequently did not remember how to interact with the guide once the video was ended. To address this issue and make the tutorial more useful and effective, we divided the help guide into chunks of explanations: in "Step by Step 2.0" information is provided when users need them. This change was meant also to take into consideration the fact that people tend to easily forget instructions when they do not immediately put them into practice [148]. In this perspective, a pop up is shown near the control the user has to interact with for the first time (Fig. 3.10).

Hints aiming at better assisting visitors' behaviors were added in the navigation system, too. In the first version of "Step by Step", 3D maps were used to show the user the path she has to follow to reach a given destination (Fig. 3.11a). Even if this approach was found intuitive by people accustomed to play with video games, most museum visitors found it difficult to follow, as its interpretation requires a too hard abstraction process for the users. In this perspective, 3D models were replaced by 2D maps (Fig. 3.11b), where the actual position and the destination are made explicit by a pin and the visitor can look

Figure 3.10: "Step by Step 2.0": tutorial with pop-ups

at a glance the total path on the map. The path to the next destination is shown both by a fixed red line and an animation that further explains the steps to be followed. Brief textual indications explicit the floor in which the user is (e.g. "you are at the ground floor") and the basic actions she has to take in order to reach the destination (e.g. "Reach the stairs and go to the second floor").

An in-depth testing of "Step by Step 2.0" was conducted in a real context of use, involving 21 museum visitors: users were observed when using the application and then interviewed. Results pointed out that the main functions of the new menu were generally easily found by users: in fact, when asked to perform an activity, people mostly succeeded in selecting the right button at the first attempt. This confirmed that the reduction of the number and type of functionalities made available, together with their presentation through better conceived icons, facilitated the usability of the application. Overall, just a minority of users reported difficulties in performing the tasks, and they suggested to avoid splitting the functionalities into two menus, in order to make all the functionalities always visible. Concerning the tutorial, users clearly understood that pop-ups appearing when performing an activity for the first time were hints and deemed useful to get explanations about functionalities progressively. The graphic layout of the whole application was rated positively too, and some users stated that the pleasantness of the visual design encouraged them to use the application, thus reinforcing the principle that visual appeal can support an extensive use of digital tools.

Overall, the combination of images with short texts highlighting not only the meaning of the artworks but also unusual anecdotes was highly appreciated by visitors: with few exceptions, it was found effective in communicating cultural information, fostering curiosity and providing context to the artworks. One visitor considered the information

(a) “Step by Step”: 3D navigation system

(b) “Step by Step 2.0”: 2D navigation system

Figure 3.11: A simpler navigation system.

per artwork excessive, whereas three visitors would have preferred to have even more information: this underlines that a certain degree of personalization in the contents is valued by visitors, since their personal interests may vary consistently. The new design of the navigation system allowed visitors to easily understand their position on the map and the location of their destination; however, since the system does not automatically track users’ movements inside the building, people had some difficulties in orienting themselves when moving towards the destination, finding hard to relate their physical position with the path displayed on the map. In order to understand whether the new release enabled a better user experience, 8 visitors (aged 13-45) were also asked to evaluate the new release against the first version of the application. Given that, an extensive and enjoyable access to cultural contents represents the main goal of the multimedia guide, visitors were particularly invited to express their opinions about the different models of content presentation used in the two versions of the application. Overall, the new version was frequently defined as more fluid and intuitive, and it was preferred by the totality of users: *"The direct connection of the texts with the images helped me easily understand the identity of the characters portrayed in the painting. I also liked seeing pictures providing context to the artwork"* (male, 30 years old, visiting in couple); *"I found the new version more intuitive and easier to use. It also explains contents more deeply; the pictures help you focus your attention, they suggest where to look at"* (female, 20 years old, visiting in couple). As to collect empirical evidence for these results and understand whether the new user interface actually affected visitors' behaviors, the data-log automatically recorded by the application were analyzed and compared against the data available for the first version of "Step by Step".

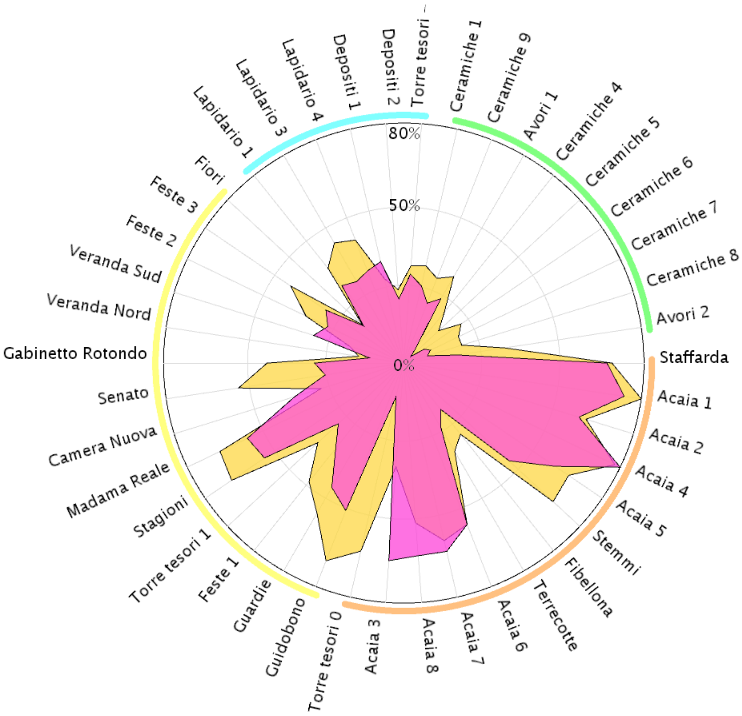


Figure 3.12: Room visits: comparison between Step by Step (pink area) and Step by Step 2.0 (yellow area)

Fig. 3.12 shows that the new release fostered a higher exploration of the venue: on average, visitors using the new release scanned 39% of the 45 visual markers deployed in the environment (calculated on about 200 visitors), against a mean of 34% registered for the old version (calculated on about 80 visitors). This means a small increase of 5% in absolute terms, but a 15% improvement in relative terms. Interestingly, the markers located on the ground floor (see Fig. 8, orange sector) - i.e. at the beginning of the visiting path - were scanned with similar rates both by users of the old version and of the new one, whereas the markers placed in other areas of the palace were framed mainly by visitors who experienced "Step by Step 2.0". This means that the new release was effective in encouraging a scattered exploration and in keeping visitors' interest, showing how a more pleasant and easy to use interface improved visitors' will to explore the cultural venue with the support of the mobile guide.

3.3 Gossip at Palace

Palazzo Madama—Museo Civico d'Arte Antica is especially renowned for its baroque facade, the building still preserves beautiful 18th-century frescoes and an extensive collection of decorative and fine arts displayed on four floors.

Even though the baroque era played a major role in the definition of the history and the art of the building, the interpretative concept of the site primarily focuses on the artworks on display: as a result, the political role played at that time by the royal Savoy family, together with the stories of the people who inhabited the palace, are not perceivable during traditional visits.

To fill this communication gap, a location-based mobile application was developed, offering visitors contextual information that could help them discover the characters, traditions, and events that characterized the palace in the 18th century. More specifically, the learning objectives set for the game were as follows: to communicate the story and the personality of Marie Jeanne Baptiste of Savoy-Nemours, the Royal Lady who inhabited the palace in baroque times; to convey information about the history of the Savoy dynasty and some of its members; to make people understand the function of the building in the past; and to explain the meaning of a selection of decorations and objects on display. With regard to the intended audience, the application was primarily conceived for teenagers; the reasons behind this target choice are twofold: firstly, no learning support specifically developed to engage this audience was available in the museum, and secondly, the evaluation of a location-based mobile game previously developed for children visiting the venue pointed out encouraging results in terms of users' engagement and degree of appreciation of the experience [153]. The older age of the target induced developers to push forward the number and depth of information communicated through the game: we decided to shift from the quiz-based approach, used for children, to storytelling, a method that was considered more appropriate to convey richer cultural contents.

"Gossip at Palace" is provided as a location-based mobile game optimized for 7-inch tablets borrowable at the ticket office. Design decisions were made taking into account the context of the particular museum and the goals intended for the mobile experience [4], together with the literature on game mechanics [70, 136] and location-based mobile games for learning [5]. Coherently, it was decided to do the following:

- provide a back-story as a basis of the game tasks to provide a meaningfully background to the experience;
- exploit role-playing to enhance visitors' emotional engagement;
- provide contextual clues linked to specific places to better capitalize on the physical position of the user;
- integrate a variety of microgames [15] challenging different visitors' skills;
- integrate rewards tightly with exploration and tasks to enhance visitors' motivation;
- balance two conflicting elements, such as competition and knowledge acquisition, by rewarding the depth and accuracy of exploration rather than short game time completion [14].

Due to the exclusively on-site nature of the game, recommended previsit activities [5] were not implemented; additionally, the lack of a Wi-Fi connection throughout the museum prevented the arrangement of activities to be shared through social networks.

3.3.1 The storytelling approach

The back-story is as follows. It is 1717, and the Royal Lady Marie Jeanne Baptiste of Savoy-Nemours, who ruled as regent before the majority of her son, believes that there is a spy in her palace; she thus asks the player to investigate and find who is the betrayer among the characters in the palace.

This story links the context-based cultural information to the game tasks. To allow users a quick understanding of the game goals and the actions required to fulfill this challenge, the back-story is presented under the form of a short video in the introductory phase: the first moments of a playing experience are vital to the whole game, as players become familiar with the game structure and rules [71], so the player was provided with the fundamental background information from the beginning of the experience.

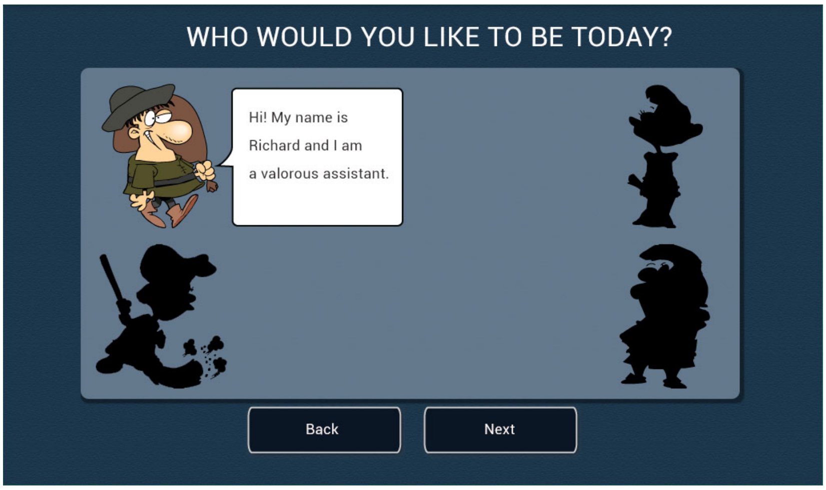


Figure 3.13: Avatar selection.

Before starting the actual adventure, the player selects her avatar among a set of four virtual characters (Figure 3.13): this choice aims to enhance empathy throughout the game and influences the following phases of the game, customizing dialogues and other information. After choosing the avatar, the game begins and the user can start her visit. The "interactive dilemma" described by Peinado and Gervas int [110] that is, the tension between telling visitors where to go or let them freely wander through the venue was faced opting for a constructivist approach [61], thus allowing them to visit the museum following their own paths. This choice was reiforced by considering visitors' preferences: recent empirical research shows that most people follow an exploratory behaviour [47], preferring to freely explore the venue even when using a dedicated mobile application [120]. Moreover, studies specifically focusing on the evaluation of mobile games developed for cultural heritage contexts pointed out that players favour visiting the venues quite autonomously, without following a preconceived route [14, 57].

The active role of visitors regarded not only their movement through the physical space but also the degree of exploration of the contents: players were given the opportunity to discover the story of the palace from different perspectives and choose to what extent deepening the pieces of information progressively provided.

To accurately identify the position and orientation of the visitor inside the museum and thus convey appropriate contents, an indoor positioning system based on the recognition of visual markers was adopted [10]. When the player scans a marker, a panoramic photo of the room, augmented with one of the 16 virtual characters that animate the game, is shown on the device (Figure 3.14). This approach was found to be particularly intuitive during our previous studies [120] and was thus integrated in the application to help users easily connect the cultural contents with the physical context of the museum. The use of real-time images rather than preloaded photos was not deemed convenient, as object recognition requires a complex processing and highly depends on a variety of conditions (e.g., light, camera orientation) to be accurate.

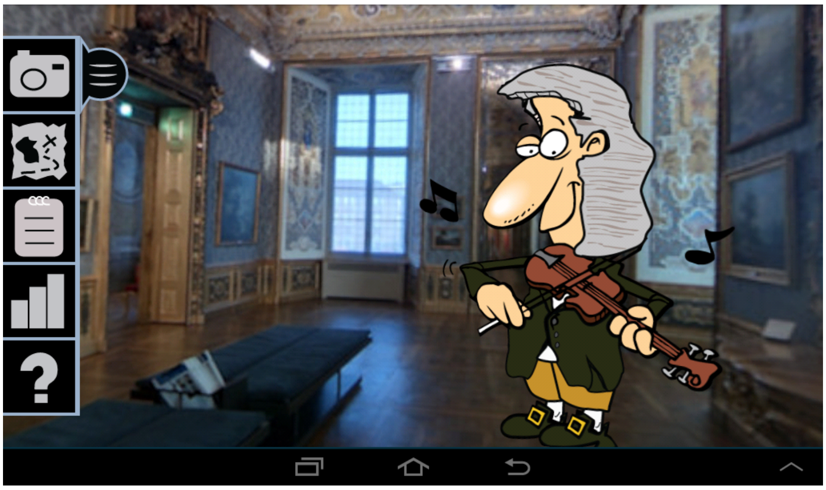


Figure 3.14: Panoramic photo augmented with a virtual character.

To further help visitors focus their attention, facilitate their orientation process, and minimize the mental effort required to make sense of the contents provided, our system was set up to automatically rotate the panoramic photo towards the point of interest described by the virtual character.

The identity of the virtual characters is defined by different genders (masculine, feminine), social status (noble, servant), and personal inclinations (attitudes, abilities, preferences, etc.): virtual characters aim to synthetically present historical data, suggesting the atmosphere of that epoch and providing teenagers with textual and visual elements that could help them better relate to that historical period. The connection of each virtual character with the room in which the user is located can either be obvious or not without interacting with the character: Palazzo Madama has undergone several transformations during the centuries, and the role of the virtual characters allows perception not only of 18th-century stories but also the functions of the different rooms of the palace at that time (e.g., the kitchens were located in the space that is now used as a storage room). By interacting with the virtual characters, players are exposed to written dialogues (Figure 3.15): following their interests, players can select different branches of information and build their favourite microstories. A finite state machine governs the creation of dialogues, proposing different sentences to choose from, according to what the user has previously chosen and attributes points according to the extent the user has followed the conversation flow.

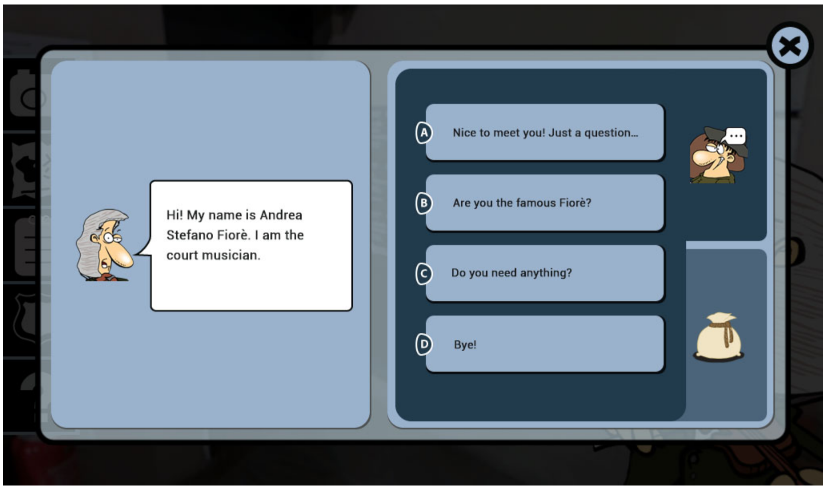


Figure 3.15: Example of a dialogue.

While designing the dialogue structure, important nodes were identified:

- overall, the storytelling adopted approach can be defined as a braided multilinear experience, as the core narrative of each dialogue branches into several directions [130].
- The binding agent between all dialogues was represented by the aim of the game finding the spy. The branching of the narrative was conceived at its microlevel that is, the single dialogues appearing when scanning the marker in a museum room.

Since the number of rooms in the museum is much larger than the number of characters and each visitor is free to visit a room many times, each character can be met several times in different places. Therefore, the system was set up to keep record of the branches of dialogues selected by the player and thus guarantee the continuity of the experience.

3.3.2 Game mechanics

To get the clues necessary to successfully complete the game, players need to earn points and achieve new levels. Coherently with the objectives set for the experience (i.e., encouraging the discovery of the building and promoting in-depth exploration of the cultural contents), two categories of scores were created:

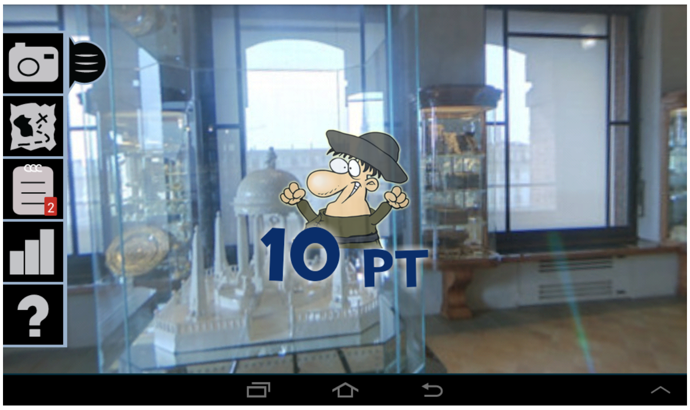
- Exploration score: This score depends on the user's movements throughout the building. To progress, the player is invited to explore the physical space and scan as many visual markers as she can.

- Sociability score: This score is based on the user's interaction with the virtual characters. Players can earn points by getting involved in the virtual conversation and answering appropriately to the depicted situation, as well as taking into account the role of the selected avatar.

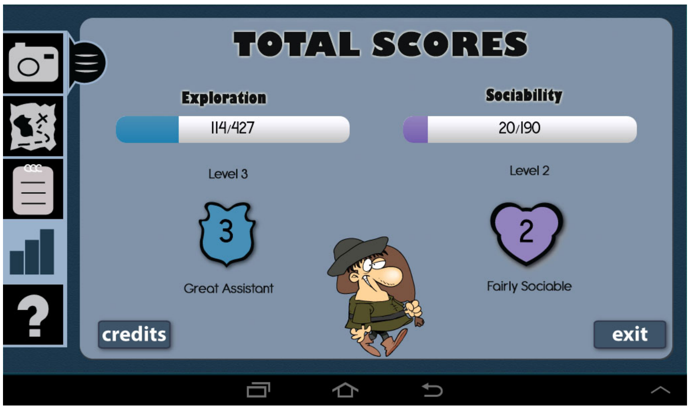
To add variety to the experience and increase the appeal of the game to hard-core players, virtual objects are scattered on the panoramic photos: users can earn additional sociability points by first collecting and then giving the appropriate objects to the virtual characters.

A variety of microgames proposing observation, reasoning, and arcade tasks [15] was also included in the game to encourage visitors' focus on the physical environment of the palace and enhance the momentary satisfaction stemming from the successful completion of activities. Solving quizzes, puzzles, crosswords, missing details, and memory activities are awarded with extra points, favouring a faster progression in the game.

To progressively reward players and foster their motivation, every time the player accomplishes a meaningful action, a triumphant version of the avatar appears, reporting the amount of points just earned (Figure 3.16(a)). Additionally, users can constantly check their advancements by browsing a dedicated section of the application showing the present score status (Figure 3.16(b)); the degree of advancement is also expressed through badges and adjectives that describe the level achieved (e.g., "Great Assistant," "Fairly Sociable"), with the aim being to enhance the player's emotional engagement with her virtual counterpart. As the player progressively explores the venue and interacts with the virtual inhabitants of the palace, she receives a clue that is useful to exclude a character among the set of suspects. To allow visitors to play with the game repeatedly without compromising the tension linked to the discovery of the spy, the betrayer is recalculated by the game engine at every match.



(a)



(b)

Figure 3.16: Score categories (a) and triumphant character (b).

3.3.3 Evaluation of the gaming experience

To understand how the location-based mobile game influenced visitors' behaviours and investigate whether it was effective in fostering enjoyment and learning, different methods of evaluation were selected by researchers and then performed by real users. More precisely, the objectives of the study were as follows:

- to understand the degree of appreciation and acceptance manifested by users towards the gaming approach proposed and towards specific components of the application
- to test the effectiveness of situated digital storytelling for the acquisition of factual knowledge
- to investigate to what extent the game influenced players' behaviours in terms of

physical exploration of the museum

To answer to the first two research questions, the game experience was evaluated through a field study entailing the participation of actual visitors of the museum, combining a short questionnaire with semistructured interviews. Overall, 37 volunteers were recruited at the museum ticket desk, asking them to freely use the "Gossip at palace" application. All volunteers were first-time visitors of Palazzo Madama—Museo Civico d'Arte Antica, and the panel was composed of 54.1% males (n = 20) and 45.9% females (n = 17), with ages spanning from 7 to 55 years. When recruiting the volunteers, it was decided to engage teenagers—the intended target audience of the game—as well as children and older visitors to test whether the use of the followed gaming approach could be extended also to other age groups.

Q1 – How much did you find the game interface intuitive?
Q2 – To what extent was it easy to understand the aim of the game?

Q3 – How much did you enjoy the experience?
Q4 – To what extent would you recommend the game to a friend?
Q5 – To what extent would you like to play a similar game in another museum context?
Q6 – How much did you feel gratified after playing with the game?

Q7 – To what extent did you find the game rich of stimuli?
Q8 – How much did you find awarding points and badges motivating?
Q9 – How much did you like picking up the virtual objects?
Q10– How much did you enjoy reading the dialogues?

Figure 3.17: Questionnaire used for the evaluation of the game.

The questionnaire (figure 3.17) was designed considering both the mobile nature of the experience [7, 56] and the educational scope of the application [40]. The questionnaire included 10 questions that aimed to evaluate some aspects of the usability of the game (Q1, Q2), the satisfaction manifested by users (Q3, Q4, Q5, Q6), and the appeal of the game mechanics implemented (Q7, Q8, Q9, Q10). Visitors were allowed to express their opinions on a seven-point scale (min. 1, max. 7). The mean value registered for the intuitiveness of the game interface was 5.41/7 (SD = 1.462; Mdn = 6; Q1), whereas understanding the aim of the game (i.e., finding the spy among a set of characters) was considered easier (M = 5.92, SD = 1.320; Mdn = 6; Q2). The variety of stimuli provided by the game was rated 5.30/7 (SD = 1.412; Mdn = 5; Q7); more specifically, the game mechanic that was appreciated the most was gaining points and badges while progressively interacting with the game (M = 5.78, SD = 1.493; Mdn = 6; Q8), followed by the possibility to discover cultural contents through the different branches of the dialogues (M = 5.59, SD = 1.279; Mdn = 6; Q10); picking up virtual objects received a lower degree of appreciation (M = 5.11, SD = 1.577; Mdn = 5; Q9). These results confirm the importance of integrating game mechanics, such as points and badges, that leverage on players' motivation and relate the experience with a sense of personal reward. Additionally, it must be noted that an exclusively virtual activity, such as picking up virtual objects, was not so much appreciated. This suggests that including tasks that entail an interaction with the real environment is a more appropriate approach for location-based mobile games, since players want to take the most of their presence in the venue.

The higher appreciation towards the written dialogues was somewhat unexpected: in fact, exploring the different branches of contents entails reading, which is a distracting and energy-demanding activity and thus not usually very much appreciated by visitors in museum contexts. The semistructured interviews indicate that the degree of interaction and personalization allowed by the dialogues contributed to making visitors appreciate an attention-consuming activity.

The positive attitude toward the game was reinforced by the answers referring to the overall enjoyment of the gaming experience (M = 5.68, SD = 1.41; Mdn = 6; Q3), the personal gratification felt by visitors (M = 5.11, SD = 1.65; Mdn = 5; Q6), the recommendation of the game to a friend (M = 5.22, SD = 1.58; Mdn = 5; Q4), and the willingness to play a similar game in another museum context (M = 5.11, SD = 1.58; Mdn = 5; Q9). Even though the reported values are quite akin, the results suggest that visitors generally had a positive opinion towards the mobile serious game approach, even if they identified some limits in the tested application, which emerged through the semistructured interviews.

To understand whether the results varied in relation to participants' age groups, we separately analysed children, teenagers, young adults, and adults' responses. Table 3.2 and figure 3.18 highlight that children manifested the highest levels of personal satisfaction (Mdn = 6.50; Q6) and enjoy recommendation of the game to a friend (Mdn = 7.00; Q4), the desire to play a similar game in another museum context (Mdn = 7.00; Q5), the variety of stimuli provided by the game (Mdn = 7.00; Q7), and the appreciation of points and badges (Mdn = 7.00; Q8). Overall, dialogues were appreciated by all age groups and especially by adults (Mdn = 6.00; Q10).

Understanding the aim of the game was particularly easy for young adults (Mdn =

Table 3.2: Questionnaire: Participants' Responses by Age Group

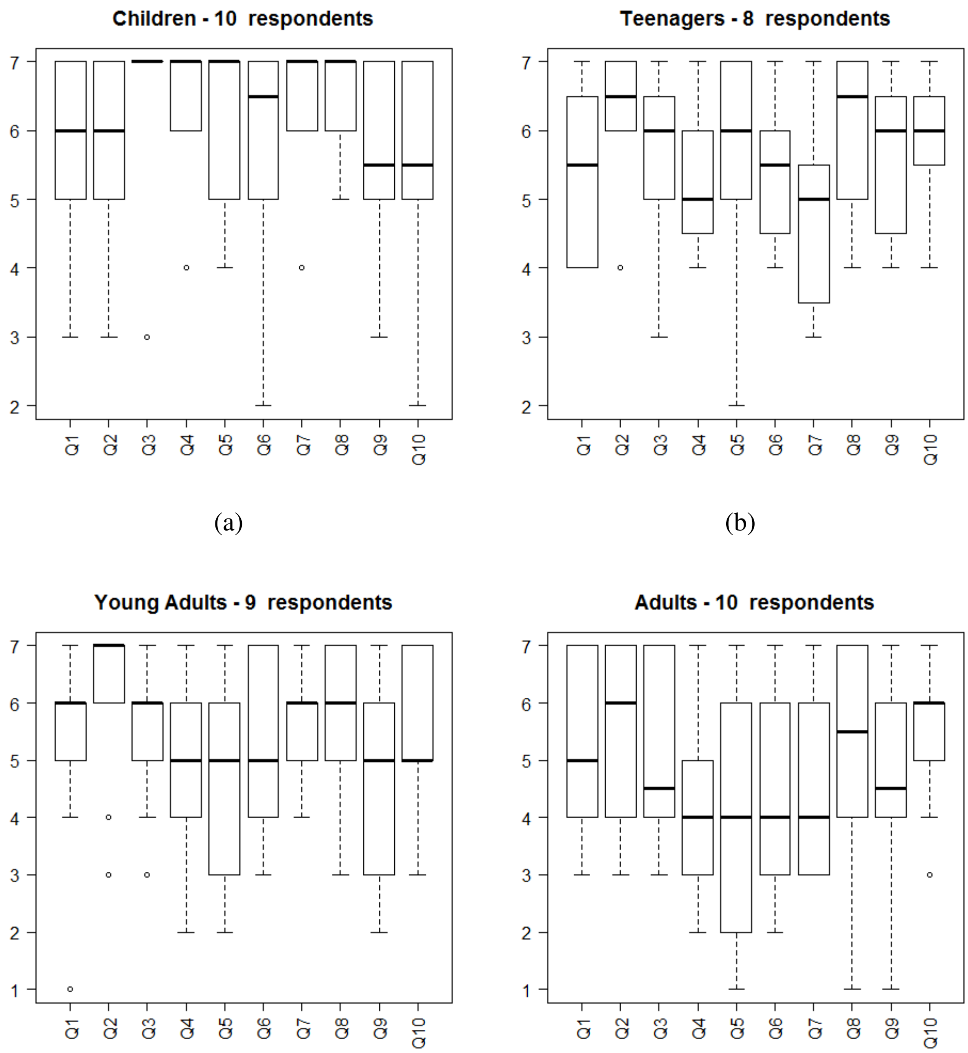
	Children			Teenagers			Young adults			Adults		
	M	SD	Mdn	M	SD	Mdn	M	SD	Mdn	M	SD	Mdn
Q1	5.7	1.418	6.0	5.4	1.302	5.5	5.2	1.856	6.0	5.3	1.418	5.0
Q2	5.9	1.287	6.0	6.3	1.035	6.5	6.0	1.500	7.0	5.6	1.506	6.0
Q3	6.6	1.265	7.0	5.6	1.302	6.0	5.3	1.225	6.0	5.1	1.524	4.5
Q4	6.5	0.972	7.0	5.3	1.035	5.0	4.7	1.732	5.0	4.4	1.647	4.0
Q5	6.0	1.687	7.0	5.6	1.685	6.0	4.8	1.716	5.0	4.0	2.261	4.0
Q6	5.8	1.687	6.5	5.4	1.061	5.5	5.0	1.658	5.0	4.3	1.829	4.0
Q7	6.2	1.229	7.0	4.8	1.389	5.0	5.6	0.882	6.0	4.6	1.578	4.0
Q8	6.4	0.843	7.0	6.0	1.195	6.5	5.8	1.302	6.0	5.0	2.108	5.5
Q9	5.6	1.265	5.5	5.6	1.188	6.0	4.7	1.803	5.0	4.6	1.838	4.5
Q10	5.5	1.509	5.5	5.9	0.991	6.0	5.4	1.424	5.0	5.6	1.265	6.0

7.00; Q2) and teenagers (Mdn = 6.50), whereas it was found more difficult by adults (Mdn = 6.00) and children (Mdn = 6.00). In particular, the use of the game interface was not found to be very intuitive by adults (Mdn = 5.00; Q1).

Linear regression analysis better explained these phenomena, pointing out that there is a significant inverse relationship between the answers registered for Q3 (r = -.427, p = 0.008), Q4 (r = -.474, p = 0.003), Q5 (r = -.496, p = 0.002), Q6 (r = -.451, p = 0.005), and Q8 (r = -.459, p = 0.004) and the participants' age. Additionally, the Kruskal-Wallis test with a post hoc Dunn's test highlighted that for Q3 and Q4, there is a significant difference in the comparison between children versus young adults' responses (p = 0.046 and p = 0.041, respectively) and children versus adults' responses (p = 0.041 and p = 0.008, respectively); a similar tendency was registered for Q7 (children vs. adults, p = 0.05). These results made it evident that despite the complex cultural contents that were conveyed through the game, "Gossip at palace" was found enjoyable by children as well, a segment that was not originally included among the target audience intended for the game. The data highlighted that the game did not meet adults' preferences, suggesting that such an approach could not be appropriate for this audience, who finds that interacting with a digital interface is a difficult and time/attention-consuming task.

Semistructured interviews

The semistructured interviews conducted with the volunteers mainly were aimed at (1) better identifying strengths and weaknesses of the application and (2) detecting whether the location-based mobile game facilitated the visitors' learning process.



(c) (d)

Figure 3.18: Box plots: distribution of participants' answers, by age group. The bold line indicates the median value

With reference to point (1), the elements that participants appreciated the most were the richness and variety of the cultural information provided, together with the role of the virtual characters, which helped visitors focus their attention on objects and decorations that they would have other- wise not noticed. The conversational tone of the dialogues, matched with a synchronized movement of the panoramic photo of the room towards the point of interest, functioned as a trigger to catch play- ers' attention and provide contextualized information. The presence of microgames contributed to an enjoyable experience as well, diversifying the tasks requested to the players. The cartoonish interface of the application represented an asset to engage children and teenagers, who got really excited when seeing the virtual characters and objects. On the contrary, the graphics were not felt as par- ticularly appealing by adults and some young adults, who considered them too childish. Interviews confirmed the important role played by levels, points, and badges in motivating players, and a success- ful/unsuccessful completion of the game contributed to participants' level of satisfaction: Playing the game was fun, and I'm so happy I've found the spy! (24-year-old woman); The game was nice, but then I got annoyed because I could not finish it (9-year-old girl).

Even if participants generally valued both the cultural information provided and the possibility to select their favourite branches of dialogues, it must be noted that users frequently mentioned experiencing "fatigue" after playing the game for more than 1 hour: this phenomenon led some of them to quit the game before finding the spy, adding to exertion a feeling of frustration emerging from not having completed the game. Volunteers did appreciate the freedom of exploration allowed by the game, but they found it too long, and the exposition to excessive information induced cognitive overload: *I used the game to explore the first two floors of the palace, but then I gave up: I think it was a bit tiring* (31-year-old man); *We explored the whole palace because we wanted to get the clues and win the game, but at the end we were very tired. The dialogues are very interesting, but at some point we started to skip them fast, without reading them: we were tired, and we just wanted to gain clues and points to win the game* (24-year-old woman).

Additionally, some young adults and adults explained that they would have preferred more information on a larger number of objects on display, suggesting that mobile applications should provide users with a great variety of stimuli to satisfy their needs. These reports induced the conclusion that the structure of the game was generally appreciated by players but that the system of clue provision needs to be better calibrated to reduce the duration of the game play to about 1 hour while keeping the free-exploration setting. Other enhancements could be represented by the reinforcement of the main narrative and by an increase in the variety of activities provided. Creating favourable conditions for the successful completion of the game would also increase the levels of satisfaction of players, and it cannot be excluded that this could encourage them to play again, since the randomness inside the game makes each match different, while exploring other areas of the palace.

Table II.

Table 3.3: Grid Used to Evaluate Each Answer

Conditions	Score
Participants did not answer or reported wrong information	0
Participants gave an inappropriate answer, but the information was correct	1
Participants gave a correct answer, specifying one detail	2
Participants gave a correct answer, specifying two or more details	3

Adults and young adults' comments confirm, as expected, that during the visit people generally want to satisfy their personal curiosity, having the chance to freely access the contents related to a variety of objects, whereas they are less inclined to deepen their knowledge about stories that are connected to a limited number of items.

Finally, interviews pointed out that whereas children and teenagers found the game suitable for their age, young adults and especially adults recommended the game for visitors up to 15 years of age; some participants declared that they would envision the use of the game for school groups particularly interested in the 18th century as an enjoyable way to explore the history of the palace during that period.

To check the achievement of the learning outcomes described previously, participants were asked to answer four questions during the interview. This task aimed to investigate whether they could recall some historical information conveyed through the game. Given that "Gossip at palace" mainly aimed to communicate historical contents that are not presented in the museum through traditional interpretive materials, it was not deemed appropriate to ask the same questions to nonplayers to understand whether the game was more effective than panels and labels in communicating cultural information.

The questions were open ended and formulated not to require a unique answer (e.g., *What can you tell me about Victor Amadeus II?*), as it was not known which branches of dialogues had been actually followed by the users. Additionally, this choice was made to not intimidate the participants and make them not feel judged. Despite these measures, 5 of the 37 participants refused to answer. If it can be supposed that in these cases visitors did not feel confident about the acquisition of new knowledge and that the game probably did not foster this kind of learning, these data also induce a methodological reflection driving towards the necessity of elaborating and integrating new methods to evaluate the results of informal learning environments. Even though previsits tests were not conducted, participants' answers were considered as a sign of new knowledge acquired thanks to the mobile game for a variety of reasons. First of all, the traditional interpretive materials available in the museum do not provide hints about the stories of the people who inhabited the palace during the baroque era. As well, the local history of the period is not usually taught in schools and is not widely known. Finally, participants were all first-time visitors and did not have the chance to attend visits led by a museum guide or other educational initiatives. To evaluate the degree of knowledge acquisition, each answer was thus assigned a score, as shown in table 3.3. Then, the total score was calculated for each participant, and performances were coded as reported in table 3.4. Answers were examined by two researchers, with an interrater agreement of 97%.

Table 3.4: Classifying Participants' Acquisition of Historical Knowledge: Categories

Total Scores Appointed to Participants	Acquisition of Factual Knowledge: Categories
0-1	L0 : Participant did not show any acquisition of historical knowledge
2–5	L1: Participant manifested a sporadic acquisition of historical knowledge
6-9	L2: Participant manifested the acquisition of diffuse but basic historical knowledge
10-12	L3: Participant manifested the acquisition of diffuse and detailed historical knowledge

Overall, 21.6% (n=8) of the participants did not show any acquisition of historical knowledge (L0), while 10.8% (n=4) manifested the acquisition of diffuse and detailed historical knowledge (L3); L1 and L2 represented respectively 32.4% (n=12) and 35.1% (n=13). These results indicate that there is evidence that the game was effective in conveying key contents (e.g. the political role of the Royal Lady and of her son, the function of the building in the 18th century...), at least for a certain number of players. The fact that some respondents were able to recall more detailed information indicates that some players meaningfully explored also the "deep branches" of the dialogues.

The analysis of participants' answers according to age groups (figure 3.19) highlighted that the majority of children did not show any evidence of learning; teenagers generally acquired sporadic and basic historical knowledge; young adults mainly manifested diffused basic learning, whereas adults' performances were more variable, nevertheless registering the highest percentages of detailed historical knowledge. Linear regression analysis pointed out that there is not a strong relationship between participants' age and their learning level (r= 0.357; p=0.30).

In conclusion, it can be stated that a dichotomy between the appeal of the gaming approach and its effectiveness in communicating cultural contents exists: on the one hand, the gaming activity was more appreciated by children and other young visitors, but it actually resulted only partially effective in fostering the acquisition of factual knowledge; on the other one, the older visitors were less engaged by the game itself, but they were

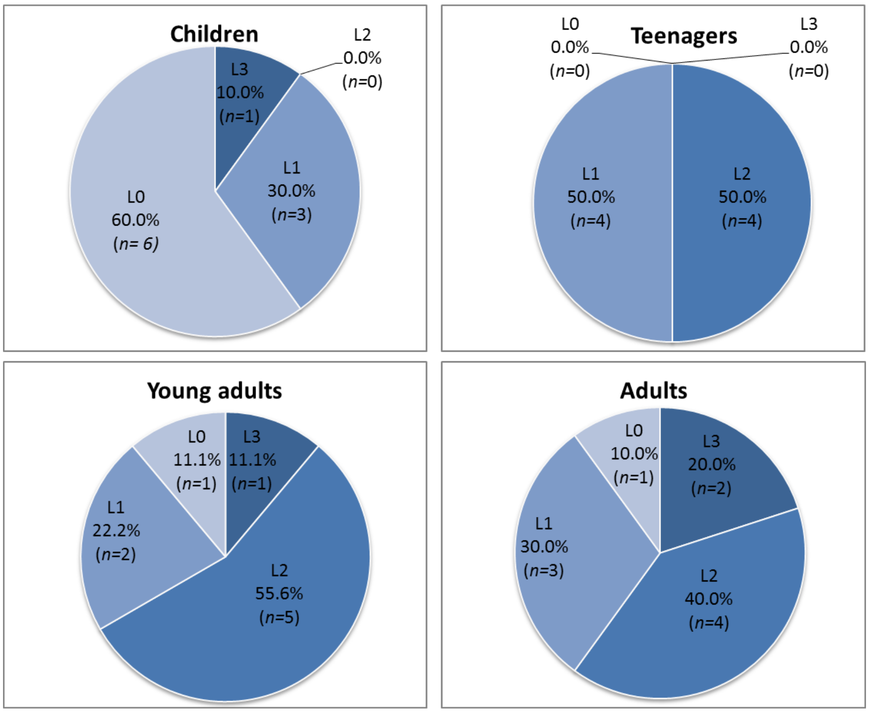


Figure 3.19: Participants' acquisition of factual knowledge, by age group.

able to process and recall more detailed information.

Interestingly, during the semi-structured interviews, a different and possibly more adequate evaluation methodology emerged. Some children reacted positively when invited to freely comment a picture of a room of the palace: in fact, they were able to make a detailed description of the ceiling decoration, also explaining the function of the room in the 18th century: *"Oh, this is the room where I met the [virtual] musician: the ceiling was decorated with children performing different games in the open air"* (10 years old boy). Given that this piece of information is not available elsewhere in the museum and that they were first time visitors, it can be stated that the game was effective in communicating cultural contents to young boys, but also that this method was more appropriate to investigate learning in an informal educational setting. This method was then successfully proposed to other participants. The descriptions made by volunteers when exposed to the pictures of the rooms included a variety of information: the simple identification of the name of the rooms; their spatial (near, opposite, etc.) or functional (bedroom, ballroom, etc.) identification; the recall of the virtual characters met (guard, gentleman, etc.); the micro-games/activities performed (puzzles, crosswords, etc.); the descriptions of the physical characteristics and of the meaning of the decorations and of the objects on display. These data highlight that the combination of different stimuli provided by the game (physical environment, virtual characters, micro-games, cultural contents, etc.) was effective in stimulating different visitors' memory skills, resulting in a higher probability to foster some kind of recall and learning.

Investigating visitors' behaviours

In order to answer to the third research question, that is to investigate to what extent the game influenced players' behaviours in terms of physical exploration, the data-log automatically collected by the system of 55 players was analysed. The parameters that were taken into account were the number of markers scanned by the users and the amount of time spent by players using the application. The analysis of the first parameter was considered as an indicator of the ability of the application to motivate players towards the progression of the game and the exploration of the palace; the second parameter was registered to understand the time length usually spent by users playing.

The analysis pointed out that, on average, players scanned 57.4% of the markers deployed in the museum (Min = 22%, Max = 100%; SD = 27%). The average amount of time spent playing was 75 minutes (Min = 30 minutes, Max = 165 minutes), with a standard deviation of about 38 minutes. These results show that players usually scanned more than half of the markers, indicating that the application was effective in fostering in the players the desire of exploring the palace and actively interacting with the content. In order to understand the influence of the application on visitors' behaviours, they were compared with data collected from "Step by Step".

The compared analysis of the data-log highlighted that 63 users of "Step by Step" scanned the markers with a mean rate of 35.75% (SD = 17.31%): this result clearly shows that the game was more effective than the traditional application in fostering visitors' will of exploring the palace. The average time spent in the museum is 97 minutes, with a standard deviation of 62 minutes.

A deeper analysis of the data-log shows that most users of both applications spend their time on the ground floor and on the first floor of the building: this phenomenon is generally observed also for people visiting the museum by themselves, and it can be related to the different nature of the collections displayed and to a natural decrease in the visitors' attention, regardless of the digital support employed. However, the analysis of the percentages of users that interacted with the single markers placed in the different locations pointed out that the game was more effective than the multimedia guide to encourage

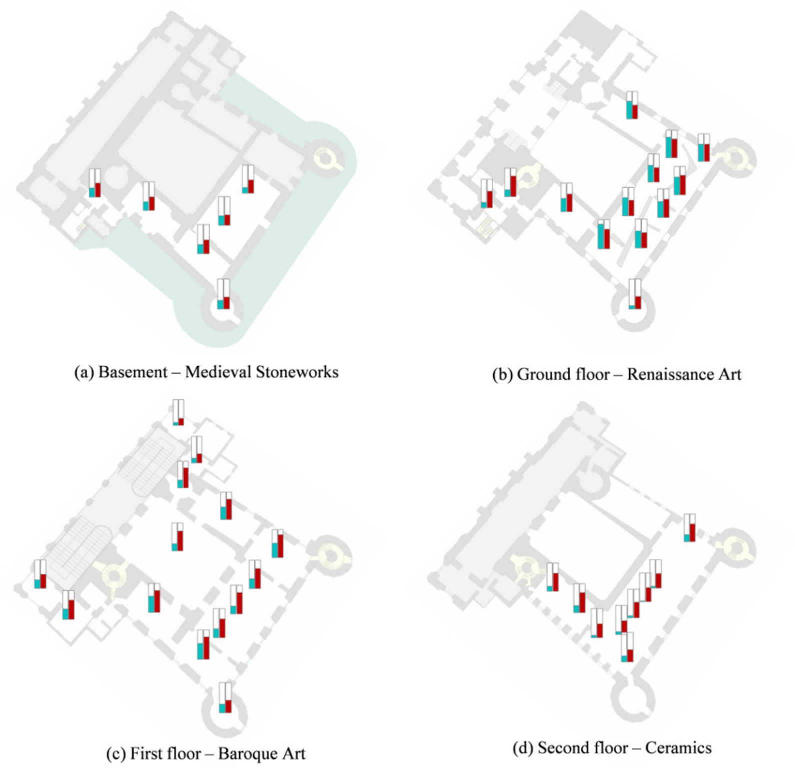


Figure 3.20: Comparison of scanned markers at the different floors: red bars represent users of “Gossip at palace” while cyan ones represent users of “Step by Step”.

players to explore also the basement and the second floor of the building. Figure 3.20 shows the comparison of scanned markers at the different floors of the museum. If we exclude the ground floor, users of “Gossip at palace” tend to explore with a higher rate all the areas devoted to museum exhibitions, especially the less prominent ones. Overall, the combination of the results stemming from the analysis of the data-log and from the evaluation of the knowledge acquired through the game suggests that “Gossip at palace” promoted an exploratory style of visit, where players visit a large number of rooms but mainly retain only a basic level of information.

3.4 Intrigue at the museum

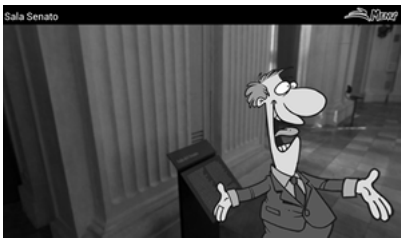
“Intrigue at the museum” is a single player game and its plot is to find a thief in the museum among a set of virtual characters. Clues are given to the player as she solves riddles after scanning tags deployed in the building. Coherently with a constructivist approach, it was decided not to suggest a defined path to follow, but to allow children freely explore the museum environment, according to their interests and family's agenda.

Overall, the application was structured around two key-points: exploration and tasks. Location aware applications aim to contextualize learning activities by interaction with the surrounding environment [109]. Location is used to provide contents based on the position of the learner. The main benefit of this kind of applications is that they make the user explore the pervasive learning space, in our case a museum.

Besides exploration and contextual information, "Intrigue at the museum" pursues also the goal of making a visit at the museum enjoyable for the young visitors while preserving the educational contents of such an experience. Motivation is a strong lever and very important in learning activities that can take profit of gamification principles and Task Based Learning, a learning method that relies upon practical activities to construct knowledge and develop skills [12, 151].

(a)

(b)



(c)

(d)

Figure 3.21: Game's main menu (a), marker for the location aware system (b), example of a guard of the museum (c) by touching the star, the player gets access to the mini-game (d)

The first screens of the application show the mechanics and the rules of the game. The main menu (figure 3.21) gives access to the game statistics, the progress, the clues already collected and the list of the suspects (Fig 2.a). This first version is only in Italian but in the future there will be also an English one. Selecting the "Explore" function (figure 3.21) and scanning a tag (figure 3.21) with the camera of the devices, a 360° view of the current room, augmented with a virtual "museum guardian" and some space clues, is presented to the player.

Interacting with the character, (figure 3.21), the player receives information on the history of the palace or on works on display in the room. Then, the player has to solve a mini-game that is related to the knowledge she/he has gained or that involves interaction with a work of art on display in that particular zone (figure 3.21).

These mini-games are all related to the museum master-pieces as their goal is to make the user look at them under a special perspective that makes it both interesting and fun. By solving these riddles the player earns a "clue card" containing a piece of advice on who is or who is not the thief.

The mini-games were developed following the paradigm of Task Based Learning, and can be classified into three main categories:

- Observation tasks, pushing players to carefully observe the masterpieces looking for the details needed to solve the game
- Reasoning tasks, where initial clues, such as temporal information, factual details and so on, have to be absorbed by players in order to solve the riddles or quizzes
- Arcade tasks, used to provide observation stimuli entertaining the players with animated graphics and quick interaction

By finding the thief the player earns a "detective certificate". In order to achieve this result almost all the building has to be explored for collecting the clue cards.

3.4.1 Evaluating engagement as a trigger for social knowledge in pervasive learning systems

In order to test the application and assess its efficacy with respect to the preset objectives, evaluation was conducted. Coherently with the theoretical framework presented in the previous sections, evaluation aimed at investigating different aspects of the user experience, including the most or less appreciated game mechanics, the degree of unobtrusiveness of the technology, the level of engagement and social interaction facilitated by the application.

When developing the evaluation framework of analysis, two theoretical models were combined and integrated: Koole's model was taken into account with respect to mobile learning [76], whereas Falk and Dierking's model was applied since contextualising informal learning experiences in physical environments [48]. Considering that the mobile application was developed to convey a m-learning experience situated in a museum context, it was deemed appropriate to integrate these two partially overlapping models, each providing an original element to the combined framework of analysis: the first introducing the device aspect, whilst the second including the physical context (Fig 3.22).

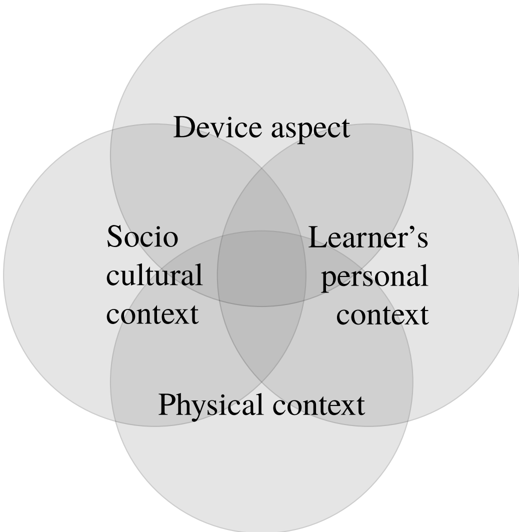


Figure 3.22: Museum experiences mediated by m-learning tools: a contextual framework of analysis

With this model in mind, research questions were addressed following a mixed-methods approach combining quantitative and qualitative research. Unobtrusive observations were deemed as the most appropriate method to investigate young visitors' behaviours and identify patterns of interaction with the device, the museum environment and group members.

Adults accompanying children and teens having used the application were asked to fill a questionnaire in after the visit, in order to collect a set of perceptions about the level and kind of engagement manifested by young visitors when playing with the game. Moreover, questionnaires served as a trigger to start conversations about the game with visitors: in this occasion, young participants' opinions about their user experience were collected too, helping the interpretation of the data collected through other methods. It was decided not to investigate the factual acquisition of new knowledge since it was deemed not appropriate for an informal learning setting such as a museum: in fact, methods of assessing knowledge could be perceived as similar to the ones adopted in formal learning settings such as schools.

Unobtrusive observations: results

Table 3.5: Analysis of the engagement manifested by the partecipants:some examples

Characteristics	Verbal indicators	Non verbal indicators
Sense of self-accomplishment or disappointment	"Wow, well done!", ”Yes!” ”This task is difficult”, ”I am a genious”, ”Umpf”, ”I've made a mistake”	Raising hands, jumping . . .
Intention to play non-stop	”Please wait, I want to accomplish this task”, ”Jut two clues and I'll be ready to find the suspect”	Absence of behaviors and activities such as manipulating personal objects, being thirsty or hungry, etc.
Curiosity	”What is this?”, ”Where it is?”, ”Let's go and discover another tag!”	Looking around, gazing at specific objects, walking fast in order to find other tags and discover further works of art
Attachment to the device		Keeping the tablet active throughout the visit
Short-term memory	”We have already explored this room”, ”This object looks like the one we've just seen”	

During the evaluation phase, 30 young visitors were unobtrusively observed. Individuals were randomly selected in the museum venue among children and teenagers clearly holding a tablet borrowed at the museum entrance. The main goals of the evaluation conducted through this method were the following: measuring the degree of engagement manifested by participants; identifying patterns of social interaction encouraged by the game; testing the unobtrusiveness of the technology and the degree of purposeful interaction with the museum environment fostered by the application.

In order to understand and code players' behaviour, key-indicators of engagement were identified: coherently with the theoretical model described above, indicators of engagement were selected among contributions focusing both on educational computer games [101] and museum learning [16]. Starting from visible characteristics of engagement, a list of verbal and nonverbal indicators was elaborated (Table 3.1).

Results pointed out that 83% of young players revealed one or more signals of engagement, with the most frequent be-ing hunting tags in the museum, walking fastly, pointing at tags while saying aloud sentences such as: ”Look! There's another one (i.e. tag) over there!”; ”Let's go and find another one!”.

A positive and purposeful interaction with the works of art on display, detected through the monitoring of behaviors, gestures and conversations, was registered for 56% of the players ob-served. In the 20% of the individuals observed a non-desirable behaviour was recorded: children/teens were so concentrated on the game that barely paid attention to the museum environment, suggesting that technology was obtrusive for this sample of users. The rest 24% did not show externally detectable signals of purposeful interaction with the works of art on display instead, even though a meaningful interaction can not be excluded.

The analysis of verbal and nonverbal indicators also pointed out that a positive interaction among young players and adult companions/peers was registered at least for 73% of the sample observed. Positive interaction was identified both through the detection of collaborative behaviors (i.e. adults or peers helping children to solve specific tasks; adult companions gazing at the tablet to follow their children's activities; physical proximity between children and other members of the group) and conversations such as: "You have to match these items"; "We need to find this. Let's get closer, so that we can look better at the painting". The social sharing of the experience was particularly intense among peers: in fact, collaboration was identified in 10 of the 12 observed groups including more than one child/teenager; apart from behavioural patterns of collaboration similar to the ones described above, sentences such as the following represent evidence of purposeful collaboration: "Come here, I will show you how to do it"; "Do you need help?"; "Now it's your turn"; "I think that we'd better do this"; "Why don't we do this?". The data have thus pointed out that the mobile game was effective in fostering conversations and collaboration both between adults and children and couple or small group of young participants.

Even though it is not possible to state to what extent the engagement excited by the gaming experience was effective in fostering learning, evaluators took notes about players' conversation, providing evidence of the learning potential of the mobile game. For instance, a boy reported to his mother that "All the female figures painted on the ceiling have the same expression and represent the Royal Lady", which is a piece of information that could be gained only through the playing experience.

Questionnaries

During the experiment, 81 questionnaires filled in by adult visiting the museum with the children who played the game were collected. Data referring to the sex of young players report similar percentages for boys and girls, with a slight majority of females (54%). Even though the application was conceived for children aged 7 and above, the game was occasionally played by younger children too, under the strict supervision of adults. The age of participants thus spanned between 4 and 16 years, registering a peak for children aged 10. If on the one hand this distribution may reflect the demographic trend of children actually visiting the museum, on the other one it also suggests that the use of a game in a museum context was felt more appealing by families with children aged 8-12, coherently with the target audience considered by developers when designing the application (Fig. 3.23).

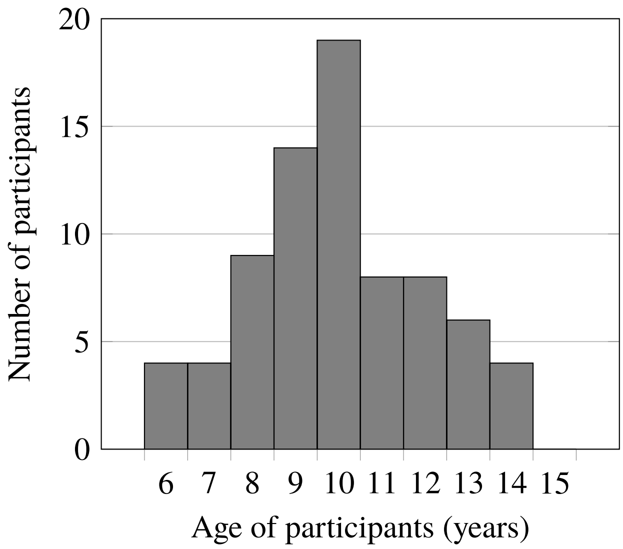


Figure 3.23: Age of Participants : frequencies

In order to have an insight of the emotional engagement manifested by young players, adult companions were asked to define the feelings of children when playing with the game: in order to collect comparable results and facilitate the process of answering to the whole set of questions included in the questionnaire, a list of adjectives was provided. Adults had the chance to choose any adjective they felt relevant, and they were allowed to write any other adjective describing their children's feelings. Results show that selected adjectives had almost exclusively a positive connotation, indicating the effectiveness of the game in fostering a positive emotional engagement towards the experience (Fig. 3.24). Interestingly, when negative adjectives were mentioned, they were anyway associated with positive ones, with the exception of only two occurrences.

The fact that the gaming experience was mainly perceived as positive and effortless may indicate that "Intrigue at the museum" was effective in balancing challenges and participants' skills [34, 105], suggesting that the design of the game was appropriate for

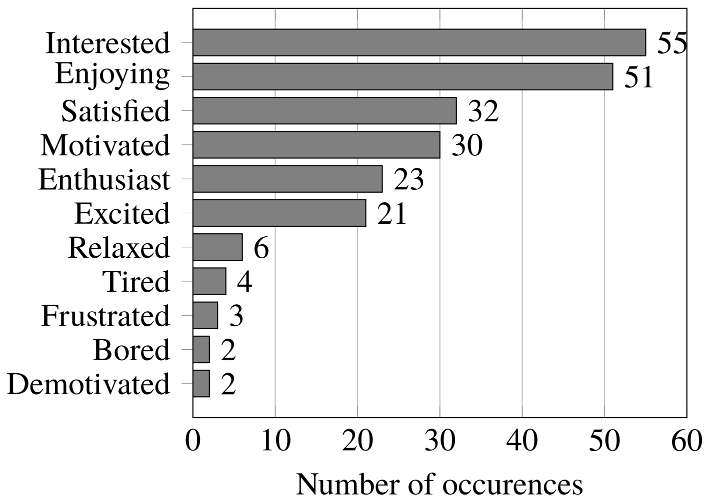


Figure 3.24: Adjectives describing players' feelings

the target audience.

Opinions verbally expressed by children and adults when commenting on their answers underline the importance of carefully design reliable game mechanics that meet visitors' expectations: in fact, disappointment was mainly due to the presence of non-active tags and to the inability of successfully scanning tags placed in dark spots, resulting in a lack of access to new challenges. In addition, the random possibility of not getting clues after the successful completion of a challenge (e.g. quiz, puzzles...) was considered frustrating too.

According to adults ' opinions, the aspects of the game young visitors appreciated the most were the solving of challenges and the tag-hunting. A smaller percentage of participants mentioned the general aim of the game (i.e. finding the suspect) as particularly valued, whereas just a minority stated that children and teens did appreciate information concerning the history of the palace and the museum collections (Fig. 3.25).

These results indicate that the game mechanics were effective in facilitating an enjoyable exploration of the museum as a physical context and that the design of puzzles, quiz and riddles that leveraged on players' sense of self-pursuit was an element of success, too. Data not only identify two areas of future improvement in the story-line and in the cultural content conveyed through the game, but also strength the belief that cultural content should be more deeply integrated in the game mechanics, in order to maximise the learning experience young visitors are unconsciously drawn to thanks to m-learning tools[122].

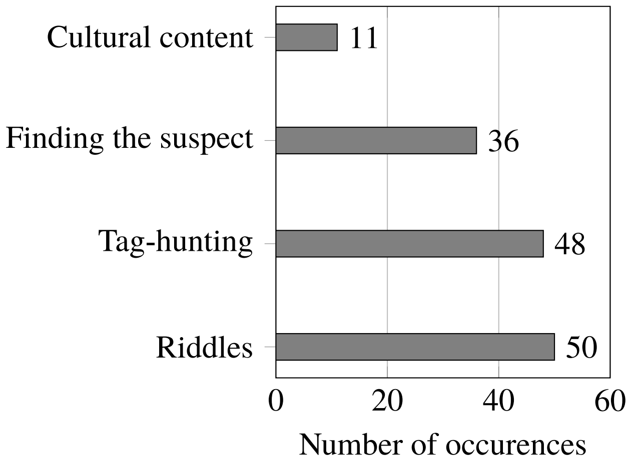


Figure 3.25: The most appreciated elements of the game

Coherently with the theoretical framework described in the introduction, a welcome result emerging from the evaluation was that playing in the museum was a socially shared experience (Fig. 3.26): in fact, data collected through questionnaires pointed out that children and teens mainly played with adult companions (46%) and - if present- peers (31%).

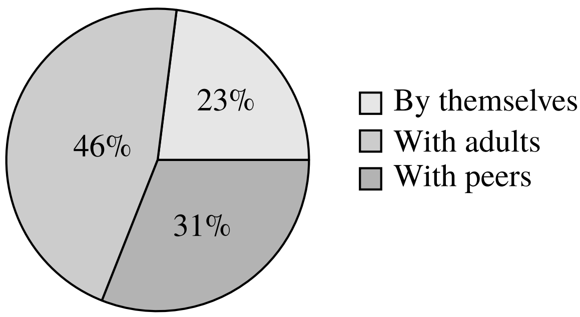


Figure 3.26: Young visitors mainly played...

An in-depth analysis of social interaction patterns pointed out that young visitors mostly shared with adult companions their feelings, the description of the challenges and the cultural content provided. Children and teens asked for adults' help especially for answering to quiz (85%); other riddles were solved with a less degree of external help (62%), instead. This suggests that quiz concerning cultural content were felt as more challenging and forces a reflection about the dynamics of effectively communicate cultural content during the gaming experience.

Since the game was developed to foster a meaningful and deep exploration of the museum context by players, the amount of time spent by participants in the museum was registered by researchers. The average amount of time spent in the museum was 1 hour and 47 minutes, being 41 minutes the minimum and 3 hours and 56 minutes the maximum: these results show that on average players spent in the museum an amount of time appropriate for the completion of the game. Considering that previous studies pointed out that the average permanence inside the museum manifested by visitors was 1 hour and 20 minutes [19], it can also be postulated that the game actively contributed in stimulating a longer permanence inside the museum. In order to test this hypothesis, further studies including control groups and focusing on the amount of time spent by families inside the museum will be needed. However, comments provided by adult companions while filling the questionnaires in further support this hypothesis: ”We've never been in a museum for so long!” (mother of a 9 years old girl); ”We came to the museum to visit the panoramic tower, but then we've started to use the mobile game and we've explored the whole museum” (father of a 10 years old girl).

3.5 Conclusions

This Chapter was dedicated to MusA, an advanced multimedia system capable of supporting museum visitors with navigation information and cultural contents related to the artworks or places in their surroundings. MusA offers a set of location-based services, relying on a vision-based approach to detect users' indoor position and orientation. The combination of indoor navigation, path communication, contextual content delivery and exhibit management on a unique system, turned out to be a reliable and effective way to enhance visitors' cultural experience. Evaluation focusing on the usability of two mobile applications, based on the MusA framework and deployed in a museum, pointed out the overall appreciation of the services and the multimedia resources provided to enhance the visit. In particular, the high degree of satisfaction and engagement manifested by young visitors with regard to a mobile game addressed to children stressed the edutainment potential of gamification approaches based on location-based systems, suggesting how mobile applications could help museums turning into pervasive learning environments and enhancing visitors' cultural experiences. MusA has shown itself to be a flexible and rich tool that allows the rapid prototyping and development of mobile guides for museum and cultural sites. Despite that, some critical points were identified during the evaluation of the test-cases.

While the cooperation required to activate a vision-based positioning system has not been perceived by our testers as a disturbing action, in some cases they reported problems to understand the navigation clues. This highlights a known issue, the proper communication of the path to follow, indicating that further research in this area is necessary. Further improvements are also required in the design of the application interface, since some users reported a cumbersome browsing of the different functionalities offered. Finally, the thematic paths should be carefully studied to meet the visitors' expectation and interests and that the contents, in particular the texts, should be fully adapted to the physical characteristics of the devices, the target audience and the context of use. These are not mere design problems, but require improvement of the communication between all the actors involved in the development process, expressly fostering the involvement of curators and cultural domain experts in the design cycle.

The second version of "Step by Step" proved that enhancements regarding the information architecture, interaction model and visual design of a museum mobile application can lead to a higher degree of use of the digital tool, supporting visitors' curiosity and exposing them to a larger number of learning stimuli. The results of the comparison analysis are useful to identify recommendations for designing an effective museum mobile guide. Firstly, the interface needs to present a limited number of essential functions, to simplify users' decisional process. Secondly, contents must be specifically conceived for a mobile consumption: this means not only that they must be appealing and well readable on a small digital screen, but also that they must be easily accessible in a context where time resources are limited and the user is free to move. Finally, the cultural contents need to be structured to allow the user to access information according to her interest: with this regard, adaptive and recommendation systems could represent a valuable solution. Then, the progressive disclosure principle needs to be followed when designing the tutorial tools, not to overwhelm visitors with information, and the navigation system should either take advantage of technologies that automatically track visitors' movements inside the building or adopt a layout that does not require an excessive abstract process to be interpreted.

The "Intrigue at the museum" experience has shown that location-based mobile games may represent a valuable m-learning resource in the museum scenario, since a careful design of the proposed activities can limit the obtrusiveness of the technology and facilitate engagement, a precursor of learning. Given these results, a future step of research will be measuring the acquisition of factual knowledge, asking children to participate to pre and post visit tests. Nevertheless, the positive feelings manifested by participants during the gaming experience and the significant amount of time spent at the museum when playing suggest that the use of the application was successful to achieve a desired learning outcome: making children want to explore the museum environment and fostering a positive attitude towards the exploration itself. In order to take into deeper consideration the mobility of the learner, future areas of development could be represented by providing connectivity to the devices, so that some elements of the gaming experience could be shared through social media platforms and translated to the everyday life of the learners.

With "Gossip at the Palace" we investigated to what extent a location-based mobile game with educational purposes has been appreciated by an audience segment, such as teenagers, providing evidence that an approach of this kind is not only generally enjoyed by this target but also can foster the acquisition of historical knowledge, at least at its basic level. Evaluation has pointed out that the digital storytelling gaming approach offers significant learning potential, and the appeal of the story is capable of overcoming fatigue related to the reading activity. Results stemming from the evaluations have pointed out that the use of the game "Gossip at palace" could be extended either to children or adults, depending on the objectives the museum prefers to prioritize: in fact, on the one hand, the game mechanics excite the enjoyment of the youngsters and thus satisfy an entertainment goal, and on the other hand, the communication of cultural contents through storytelling seems to be effective, especially with adults.

These considerations confirm what the literature frequently points out—that balancing the entertainment and learning component is extremely challenging, especially when considering the needs and characteristics of a large variety of audiences. The analysis of the data log automatically collected by the mobile system shed light on the influence of the mobile game on visitors' interaction with the cultural contents and the environment: in fact, the game proved to be more effective than a multimedia mobile guide to stimulate users' curiosity and will to scan the visual markers deployed in the museum, inducing them to explore even the less prominent exhibit areas. The adoption of a mixed-methods perspective in the study also allowed other lessons to emerge. Firstly, it was found out that the communication style played an essential role in users' perceptions and thus needs to be calibrated carefully. Some adults particularly refused to try the game as soon as they had a quick look at the application, saying that the game presented a layout that was too childish. Thus, a cartoon-like style that stimulates children may prevent adults from using the game nullifying the learning and entertaining potential of such an application.

Secondly, game length should not be overstretched: physical fatigue, time restrictions, and cognitive overload may influence visitors' intentions to actively explore cultural venues, regardless of the appeal of the game mechanics and the stories told. Abandoning the game before its actual end leads to a sense of frustration that compromises the experience. According to the users, an optimal balance between content provision and the keeping of user's attention should be about 1 hour. Thirdly, the adoption of game mechanics entailing the acquisition of points and badges fosters visitors' motivation and will to explore the museum environment, not only to satisfy curiosity but also to enable a sense of personal reward. Finally, it was found that traditional evaluation methods are not fully appropriate to investigate the mobile learning taking place in informal educational settings: as a consequence, new approaches capable of both capturing the acquisition of knowledge and investigating the changes in attitude and awareness are thus required.

The next Chapter of this thesis focuses on indoor positioning technologies. It will present in detail how the user's position is detected, methods and technologies, and how this systems can be used to offer location based services.

Chapter 4

Indoor positioning techniques

Most of us have had on their hands a map like the one shown in figure 4.1. This image is taken from a Louvre Museum brochure and presents thematic areas composing the first floor of one of the most visited museums in the world.

Figure 4.1: Map of the 1st floor of the Louvre Museum in Paris, France.

The map clearly shows that there are 4 different areas. Within each area the rooms are numbered and this helps when trying to locate oneself inside the museum. But there are no details that could help navigation inside the building. And there cannot be. It is not the fault of who designed this map, it is because the Louvre is approximately 550m long and almost 300m wide. The museum does not cover all the area but with almost 55,000 m^2 it represents a very big area to cover. A brochure of 5 pages is not enough to put all this information and carrying a book around just for orientation purposes does not seem as a proper solution. Better results could be obtained with a digital version of the map but even in that case visitors would have to orientate themselves in the digital version if no positioning system is integrated with the digital guide.

Indoor positioning is not useful only for museums. It could be very helpful in airports, shopping malls and in general almost anytime we find ourselves in big complex locations. Situational aware scenarios also need to know where the agent is in order for the system to act properly.

With its Indoor Maps offering Google has already started to provide indoor positioning functionality to 10,000 locations around the world [1]. Their main positioning technique seems to be WiFi fingerprinting. It is the technology that enables Android phones to silently scan for wireless networks in the surroundings and determine your position based on this scans. Probably the Google Street View cars help build this huge database that maps gps location with fingerprints of available wifi networks in those locations [2].

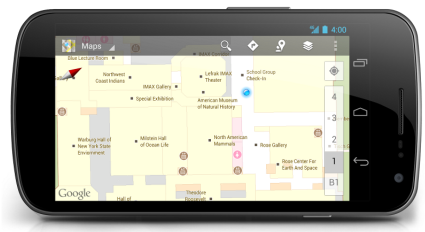


Figure 4.2: Google Maps application screenshot inside the American Museum of Natural History.

The choice of this technology leads to room/area-accuracy level results when using the Google Maps Application [3] inside the areas covered by this technology. The results are good, as seen in figure 4.2, especially if you consider that existing infrastructure was used, such as the hot-spots already available for providing internet access to visitors of those locations. But not enough for providing more powerful services like indoor navigation or augmented reality applications set in real live environments.

[1]Google Indoor Maps : https://www.google.com/maps/about/partners/indoormaps/

[2]Scanning always on : http://www.pcmag.com/article2/0,2817,2422689,00.asp

[3]Maps app on Play Store : https://play.google.com/store/apps/details?id=com.google.android.apps.maps&hl=en

This chapter represents an overview of positioning technologies while focusing mainly in indoor related techniques and systems. Their operating principles will be presented together with existing applications based on these technologies, if available. The literature research was made easier by previous surveys on indoor positioning systems such as [66, 87, 94, 126].

4.1 Classification of indoor positioning systems

A classification for indoor positioning systems was first given by Hightower and Borriello in [63]. The authors suggest three main categories for indoor positioning systems:

1. Triangulation/Trilateration : measures of distances from multiple known locations make it possible to determine the location of a certain object. When using distances as the base measuring systems then lateration is the geometrical principle that can be used to determine the unknown location. Instead, if angles are being used as the base metric to determine a location angulation is the necessary approach.

2. Scene analysis : this approach uses features of a particular scene to draw conclusions about the location of the observer or other objects in the scene. The interesting features could be visual ones, used in camera based systems, magnetic-field related ones or radio signal fingerprints. These features are stored usually in a centralized node of the system that is used to compare new features coming from the measuring devices.

3. Proximity : "nearness" to certain known locations is measured and is used to determine the observers location.

4.1.1 Trilateration and triangulation techniques

Lateration and angulation techniques exploit geometrical characteristics such as angles and distance to compute the location of certain object. Lateration computes an object's position by measuring its distance from known locations. When we know that we are X meters away from an object our position can not be evaluated because we could be anywhere in the circle with radius X as shown in figure 4.3. As shown in the image it is not possible with just this information to decide where the object is positioned in space.

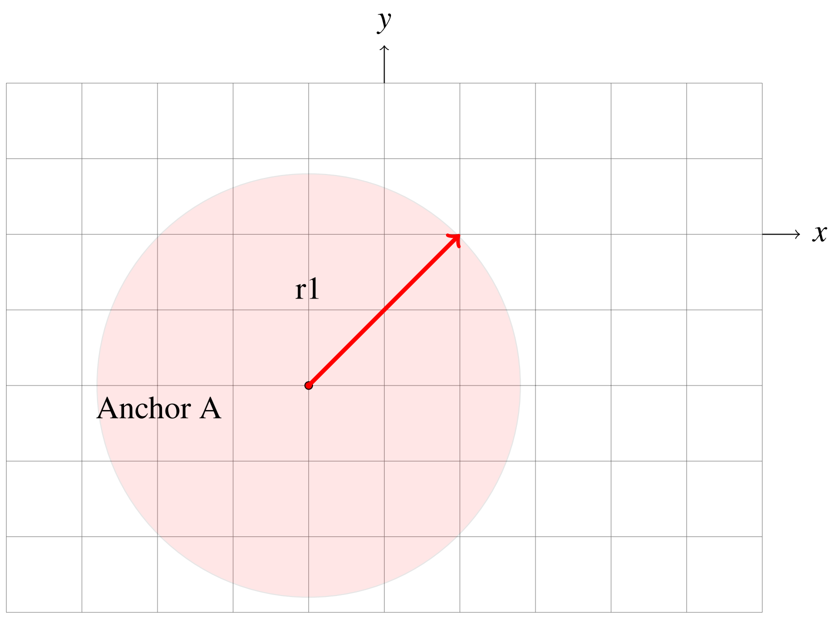


Figure 4.3: Distance known from a certain anchor node.

With two measured distances from known objects we have more information but it is still non enough. If we draw the two circles we have three solutions to the objects position problem.

- In the first case the two circles are tangent and the intersection point is the position of the object. But since the anchors have fixed positions this can be true only two times when the circles are tangent internally and externally.
- The second case is when the two circles intersect and we always have a couple of intersection points which represent possible solutions to our problem.
- The last case happens when the circles do not intersect and we have no clues on where the object might be. We just know that it is somewhere between these two circles. The last problem can be minimized by augmenting the node's density in the area in order to avoid having not covered zones or by considering the distances to have a certain error that makes it possible to enlarge or shrink this circles.

When three or more measures are available we can determine an objects position easily as shown in figure 4.4. The black area at the intersection of the three circles represents the possible position of the object. In the ideal case the three circles will intersect at precisely

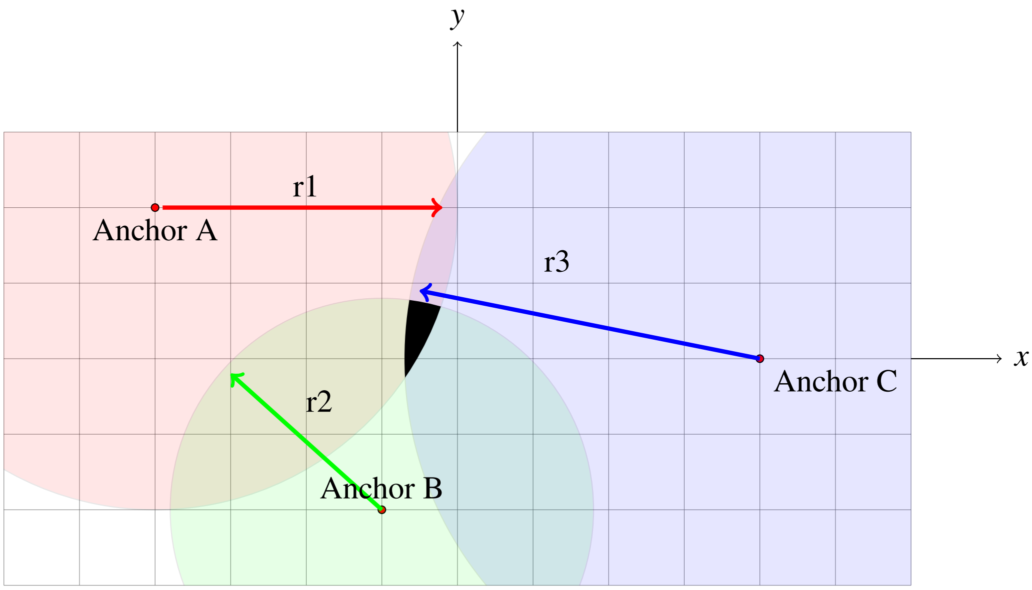


Figure 4.4: Lateration approach.

one point. When this is not verified the position of the object can be estimated by using a least squares algorithm or by using adaptive lateration [150].

In order to determine an objects position in a 2-dimensional space at least three distances are needed. In 3-dimensions 4 distances are needed in order to determine on what side of the space is the object located, with respect to the plane determined by three anchors.

Angulation

Angulation is very similar to lateration except, instead of distances, angles are used for determining the position of an object. Two dimensional angulation requires two angle measurements and one length measurement. The length measure is the one of the two nodes with respect to which angles are being computed. This is usually carried out by using special hardware that makes use of arrays of antennas to determine the angle of arrival of a certain signal. In three dimensions, one length measurement, one azimuth measurement, and two angle measurements are needed to specify a precise position.

4.1.2 Scene analysis

Scene analysis techniques exploit features of the location to determine the observer's position. Exploitable features can be visual images, signal strength measures of available access points nodes in given locations or any other measurable physical phenomena whose values can be correlated to a certain position. In figure 4.5 are presented the possible features that are extracted from images.

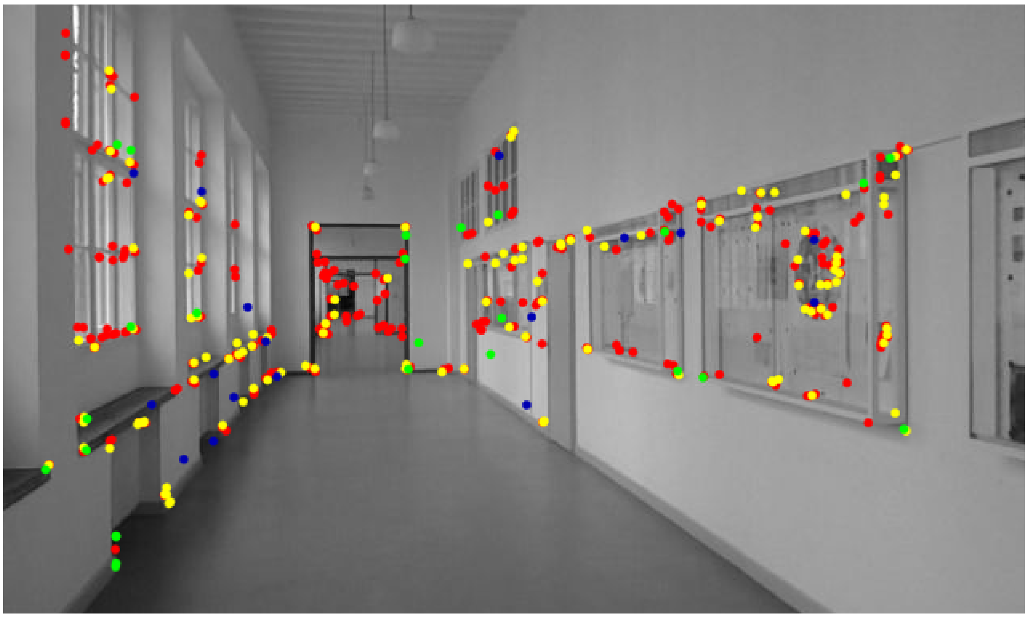


Figure 4.5: An example of scene analysis based on visual images. Image from [65]

These features can be extracted from a set of pictures taken from different positions in the environment. By comparing the features elaborated at a certain position with the ones of the datasets the position can be determined. The advantage of scene analysis is that we can use passive observations of the environment to determine where we are but this also means that any change in the environment that affects the interesting features makes necessary an update of the dataset or the reconstruction of a completely new one. It means a long and costly process of taking again the photos and extracting new features from them.

4.1.3 Proximity or cell of origin

Proximity based techniques are able to determine weather an object is "near" certain predetermined locations. Presence is sensed using physical phenomenons with limited range. RFID systems usually fall in this category.

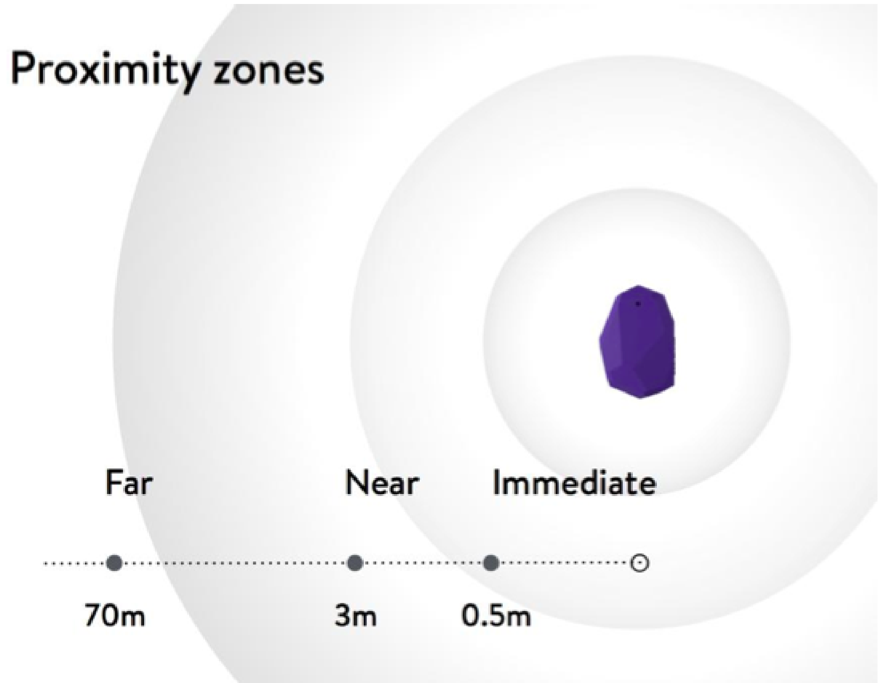


Figure 4.6: Estimote's beacon and the proximity zones

Proximity can be detected by direct contact between the observer and the observed objects, like swiping a badge, or when the observed object enters the area covered by the observer, the RFID antitheft systems of shops. Proximity knowledge means just that we are near some known position but does not provide any information on the actual position. Before further investigating indoor positioning systems the next section will be dedicated to existing outdoor technologies.

4.2 Outdoor positioning systems

Location systems were first designed to support military and commercial ships and aircrafts. The first navigators exploited the stars and measured the angles of different celestial bodies relative to the horizon. In the twentieth century this technologies were replaced by more advanced ones like RADAR, SONAR and GPS.

4.2.1 Sound Navigation and Ranging (SONAR)

Sound navigation and ranging, SONAR, was developed during the First World War for underwater navigation of submarines. SONAR uses an ultrasonic transmitter to emit ultrasonic pulses, which get reflected by obstacles or other ships. Echoes are captured by a receiver device and the time delay between the moment the pulses were emitted and the time they are echoed back is used to determine an object's distance.

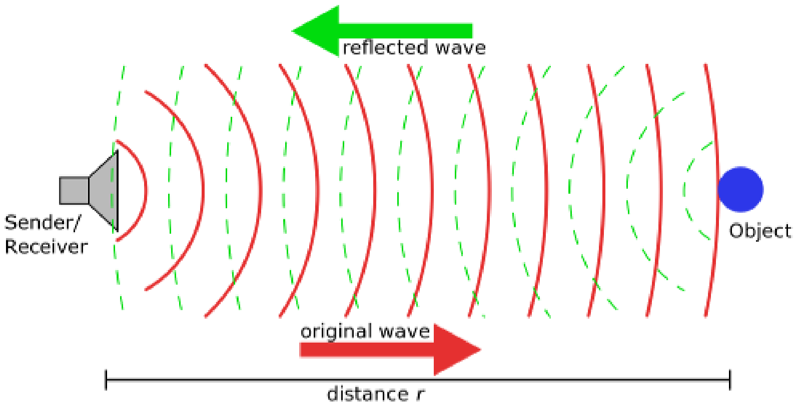


Figure 4.7: Sonar principle

Several animals in nature use this technique to locate their self in the environment. Among these the most known are bats and dolphins. Sonar technology is used to build detailed maps of the underwater world because it makes possible to estimate the depth of the sea.

4.2.2 Radio detection and Ranging, RADAR

Radar technology was developed during World War II. It uses similar principles to the sonar except that radio waves are used instead of audio ones. By using multiple radar antennas the angle of arrival of the radio-waves can be determined. Target's position is expressed in polar coordinates as we have couples of angle-distance measurements.

4.2.3 Satellite based navigation

The Global Positioning System (GPS) is a space-based navigation system that provides location and time information anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. GPS is a United States project, and other nations have or are developing similar systems such as GLONASS (Russia's own satellite system) and Galileo (a global system being developed by the Euopean Union planned to be fully deployed by 2020). These systems rely on a set of satellites deployed around the earth whose orbits are known. This information is used to know where every satellite is at a given time.

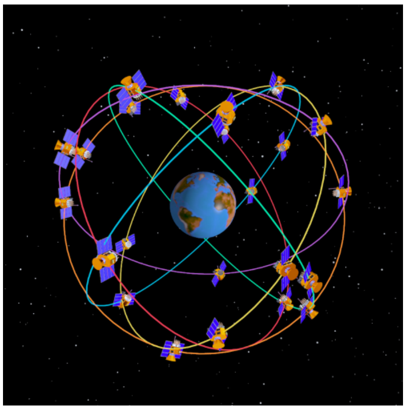


Figure 4.8: GPS satellites around Earth.

GPS is a composed of 24 satellites that perform a full earth circumference in 12 hours, passing over every point in their trajectory twice a day. This satellites carry very precise atomic clocks and broadcast all the time information regarding their current position and time. Any drift in time is corrected daily. Since the satellite trajectories are known, the receiver can use the time shifts between signals from any four satellites to solve for the four unknowns that represent the receiver's position in 3D and the current time (the time is treated as an unknown, because the clock of the receiver is not as accurate as the clocks carried by satellites).

The GPS makes use of the lateration technique to determine where the receiver is on Earth and it's precision is of about 10 to 30 meters. Furthermore in indoor environments GPS signals are subject to reflections and attenuation resulting in poor results for the positioning problem.

4.3 Indoor optical positioning systems

In this section we will describe some positioning techniques that rely mainly on camera hardware. These methods can be classified based on how the camera images are analyzed to retrieve location information [94].

Almost all optical positioning solutions are very sensitive to illumination changes, occlusions and other similar problems that affect camera based applications.

4.3.1 Scene analysis

Scene analysis techniques make use of datasets containing either images of the environment or by comparing the incoming frames of the camera to datasets of objects that can be found in that building. This leads to big datasets and thus a lot of computation power is needed to perform all the necessary transformations/analysis on the images of the camera in order to compare the latter to the features available in the datasets. The main drawback of these methods is that every change in the environment requires an update in the datasets.

In [75] the authors exploit CityGML and range image sensors to determine users location in an environment. CityGML makes it possible to create semantic models of environments. This spatio-semantic model is exploited to identify the proper room. Once the room has been identified computer vision techniques are used to determine the viewer position from the features extracted from the grayscale images coming from the sensors. These sensors provide distance information about recognized features and this makes it possible to know how far the viewer is from the objects.

Another interesting technique exploits just the floor plans and existing wifi infrastructure to reduce the analyzed area as proposed in [64]. The authors match feature points detected from a camera image to feature points in the floor plan as depicted in figure 4.9.

This technique achieves dm level accuracy. Although, the usage of very specialized hardware, the range sensor, and the need to rebuild the dataset every time there are some changes in the environment together with the need for a semantic modeling of the whole coverage area make this system suitable for usage in few specific scenarios.

The so called view-based approaches rely on sequences of images taken beforehand by a camera in the areas of interest. Once this database is built current camera images are compared against the dataset for positioning purposes. The computation load is quite intensive although it can be reduced by using other less precise techniques like WiFi to limit the considered area.

Another interesting method that can be included in the scene analysis techniques is the one proposed by [141]. Authors modify image signatures, derived from the features descriptors of the image, to work with binary descriptors that result in a reduction of the overall computation complexity and network overhead. To provide efficient streaming, the signatures are compressed by exploiting the similarities of spatially neighboring reference

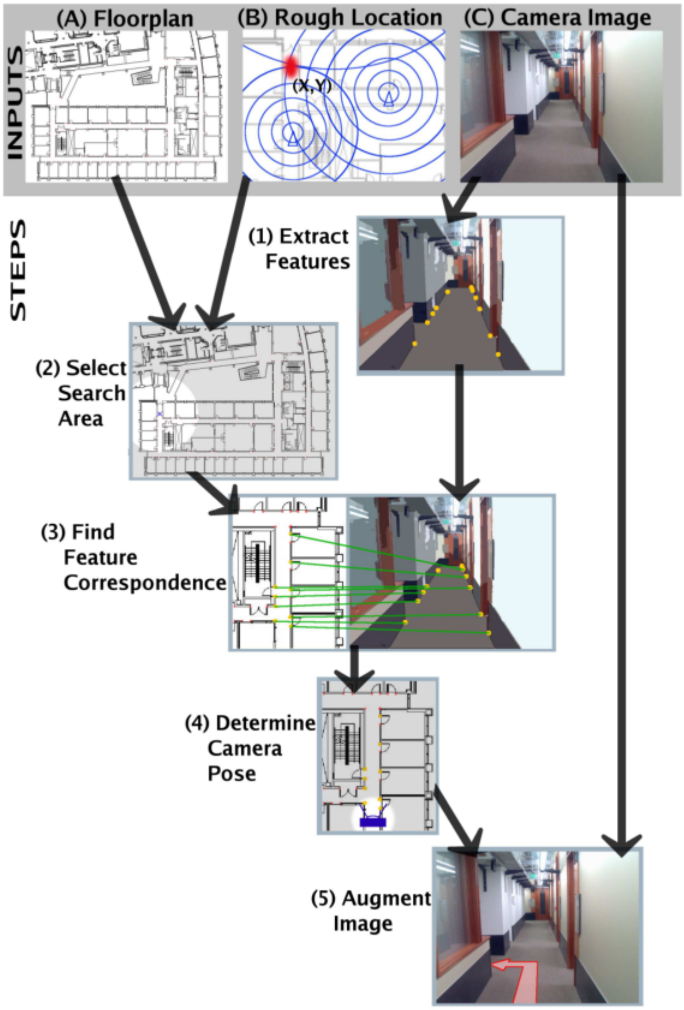


Figure 4.9: Hile's and Borriello's system diagram for calculating camera pose and overlaying information on an image from a camera phone.

images.

4.3.2 Visible light communication

In [84] the authors presented a novel method for obtaining positioning information in indoor environments. The main advantage of visible light communication, VLC, is that it does not need additional infrastructure. It exploits existing luminaries which tend to be present in a certain environment 10 times more than WiFi access points for example [84]. In Epsilon[84] the mobile device performs receiver side localization by analyzing the frames that come from the luminaries. Each light emitting diode, LED, source broadcasts a packet with identity and location information, through modulation of the LED's state as shown in figure 4.10. Epsilon uses binary frequency shift keying (BSFK) by transmitting 1 an 0 represented by two different frequencies, each one lasting for a certain duration.

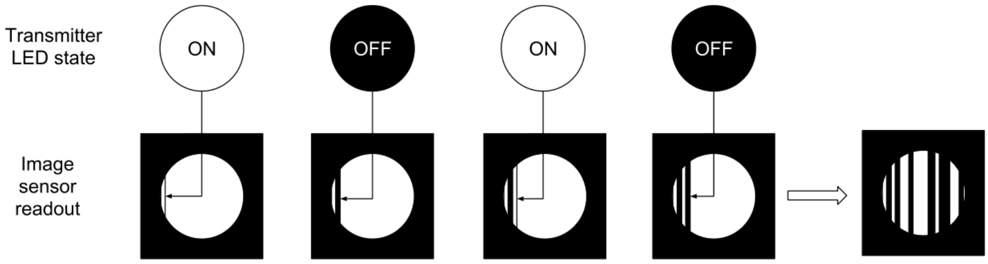


Figure 4.10: VLC data frame sample. Image from [108].

LEDs ability to switch states in just $4\mu s$[84] makes them perfect for pulse width modulation, a technique already used to provide dimming and other lightning effects. But it is not the only way LEDs can be used to communicate. LED bulbs can use various modulation schemes, such as on-off keying (OOK), variable pulse-position modulation (VPPM), and color shift keying (CSK), to embed digital information in its light. This modulation must happen at high frequencies (200 Hz or more) as lower values introduce the flickering problem, which is caused by the periodic changes in the instantaneous brightness. Low frequency flickers can make people feel sick.

In Epsilon position is obtained by using lateration once the distances from known light sources have been computed. To avoid collision between multiple sources a distributed hopping mechanism is being used. Commercial solutions are already being offered to retail markets[4].

4.3.3 Infrared

Infrared wavelengths fall out of the visible light spectrum and as such they are invisible to the human eye making this technology less intrusive.

Active Badge was designed and developed at the Olivetti Research Center in the early '90s [145]. The system is composed of a set of active clients that periodically emit pulse

[4]ByteLight indoor positioning: http://www.acuitybrands.com/solutions/services/bytelight-services-indoor-positioning

width modulated signals through an IR transmitter . This beacons are intercepted through a network of IR receiver sensors that forward the captures to a centralized master that processes the data of the "sightings", when a badge was "sensed" by the nodes. Another interesting approach based on IR transmitters is the one proposed in [1] where the system is composed on a set of IR emitting tags and a stationary stereo camera that can measure the angle of arrivals of the emitted signals and determine the location through triangulation. This system achieves almost 15cm of precision. Its main drawback is the necessary calibration of the camera to determine its intrinsic, extrinsic and stereo parameters since optical cameras are not perfect devices and each presents its own differences.

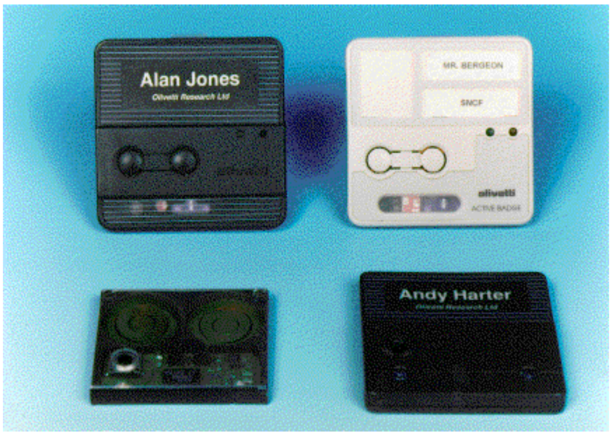


Figure 4.11: The picture shows four generations of the Active Badge. Bottom left, the first version, with a unique five bit code. Bottom right, the second version, with a ten bit code. Top left the third, current, version, with a forty-eight bit code, bi-directional capabilities, and an on-board 87C751 microprocessor.

The badges were meant to be wore on the outside of the clothing otherwise the optical path between the transmitters and receivers will be interrupted and the badges will not be "seen" by the sensors. The reported accuracy of such system is of about 6m, that is to say room level accuracy.

Infrared technology can be used even with off the shelf webcams as proposed in [1] where a couple of cameras is used to emulate stereo vision. A set of emitting tags is recognized as the system measures the angles of arrival at both cameras and uses triangulation to determine the tags position. Like Active Badge te system needs line of sight conditions, otherwise tags are not recognized.

Another usage of infrared related to positioning problems is the one that we find in

Microsoft's Kinect sensor [5]. The Kinect sensor is mainly used in entertainment applications. Since it can successfully track a maximum of 6 bodies at once, in its latest iteration, this sensor is particularly suitable as natural user interface. The human body becomes a controller for games and other applications.

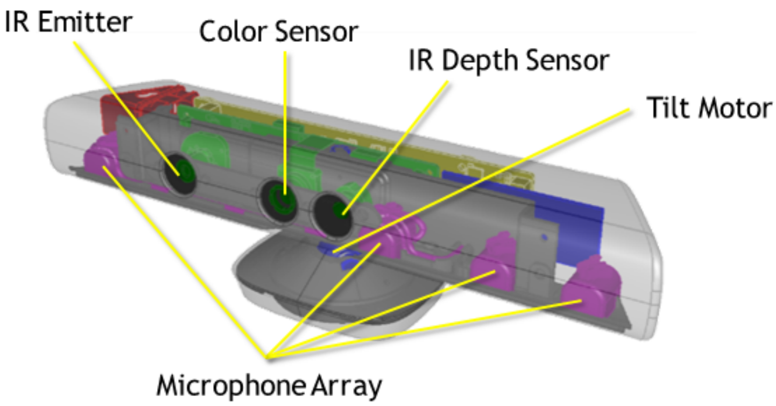


Figure 4.12: The Kinect sensor components. Picture from https://msdn.microsoft.com/en-us/library/jj131033.aspx.

The Kinect uses an IR emitter together with an IR depth sensor to detect and measure distances from objects in the surrounding environment.

4.3.4 Fiducial based positioning

Optical positioning systems that rely mainly on recognizing features of the environment lack in robustness. Varying illuminating conditions are the most common cause of this low robustness. To overcome this problem, dedicated coded markers are being used that make it possible to simplify the detection algorithm and to encode information directly into the marker. An early example of this approach can be found in [99]. By using markers with custom features the recognition algorithms are easier to implement and can take advantage of particular marker geometries when estimating the devices pose with respect to the marker.

[5] Kinect sensor specifications : https://msdn.microsoft.com/en-us/library/jj131033.aspx

The MusA marker

The MusA framework exploits a similar technique to determine the visitors position in and to provide navigation functionalities. A custom marker was designed from scratch and it will be discussed in the following paragraphs. This section is an extract from [120].

Our star-shaped marker, sketched in figure 4.13, is planar and it is obtained by combining, on a white background, two black squares with the same side, the same center and mutually rotated by 45 degrees.

The use of black and white colors for the marker guarantees an easier segmentation and feature extraction. The marker silhouette always contains, even under perspective distortion, a sequence of 16 alternate concave and convex corners. One of the triangles of the star includes a white circle, which allows to define a local reference system aligned with the marker and to univocally identify the projections of the marker corners on the image plane.

The inner part of the symbol contains the data area, divided into a regular grid of N^2 blocks each of which represents a data bit, where the extra information associated to the marker is stored.

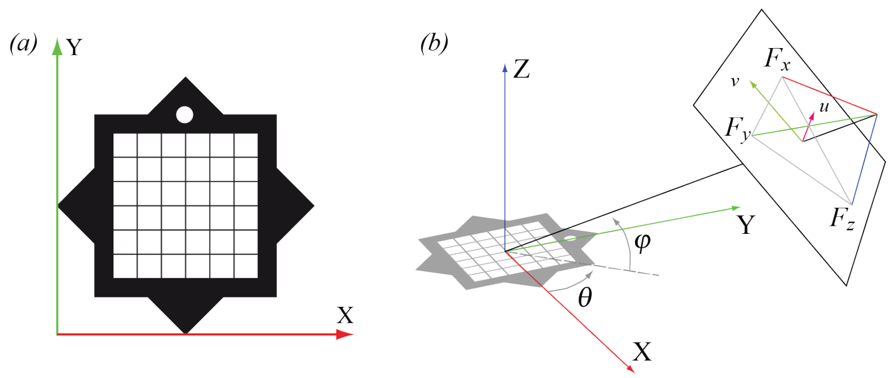


Figure 4.13: The marker used in the Step by Step applications (a) and the relative position of camera and marker (b).

Our libraries can compute the full 3D position and orientation of the camera relative to the marker, with an approach similar to the ones described in the literature. However, as stated in 3.1 we can reasonably express the visitor's indoor position and orientation with only three degrees of freedom. Thus, we designed a much lighter mobile positioning algorithm that takes advantage of the peculiar shape of our markers and of a straightforward simplification of the pose reconstruction problem.

In the following, we assume that the camera skew is null, the pixels are square and we approximate the location of the principal point with the image center. Let's choose the (u, v) image plane reference system having one of its axes parallel to the xy plane of the marker reference system (see Figure 4.13). Then, the relative camera position can be written as a function of three parameters only:

1. the distance of the camera from the marker;
2. the camera pitch (i.e., the angle φ between the camera optical axis and the ground);
3. the camera yaw (i.e., the angle θ between the projection of the optical axis onto the ground and the direction of the horizontal marker side).

Then, according to the pinhole camera model, the position on the projection plane of the three principal vanishing points (F_x , F_y , F_z) can be written as the following functions of the camera focal distance f and of the (φ, θ) camera orientation:

$$F_x = \begin{pmatrix} f \tan\theta / \cos\varphi \\ f \tan\varphi \end{pmatrix}, F_y = \begin{pmatrix} f \cot\theta / \cos\varphi \\ f \tan\varphi \end{pmatrix}, F_z = \begin{pmatrix} 0 \\ f \cot\varphi \end{pmatrix}$$

From the geometry of our marker, it is easy to obtain the image coordinates of F_x , and F_y. F_z can be computed considering that the three principal vanishing points form a triangle, whose orthocenter is the principal point, approximated as the image center. Thus, the orientation (φ, θ) of the camera can be computed as:

$$\theta = \tan^{-1}\sqrt{-\frac{F_{x,v}}{F_{z,v}}}, \varphi = \tan^{-1}\sqrt{-\frac{F_{x,u}}{F_{y,u}}}$$

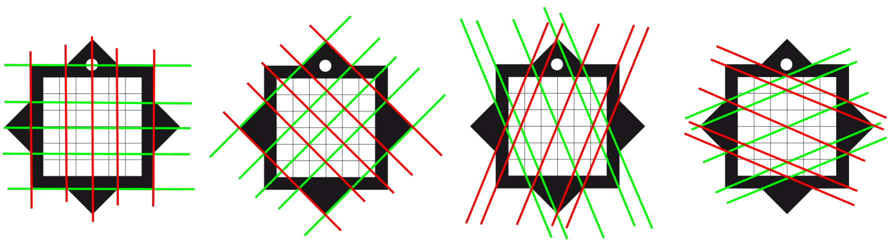


Figure 4.14: Different directions of parallel lines defined by the marker geometry.

If we guarantee the marker is deployed having one of its sides parallel to the ground, the orientation of the camera in the world reference system can be computed from the output of the device accelerometer. Finally, the distance between the camera and the marker is estimated according to the size of the marker in the camera plane knowing the focal distance f in pixel units, which can be computed from the position of F_x and F_y as described in [103].

The overall accuracy can be improved taking into account that the vanishing points of all the set of parallel directions in the marker plane lies on a line. Since at least eight of these directions can be obtained from our marker (Figure 4.14), the line best fitting their vanishing points can be used to compute a more accurate position of F x and F y and, consequently, to improve localization data.

This method is extremely light in terms of computational requirements. However, it suffers from the fact that for certain camera orientations, i.e., when the camera plane is parallel to the marker plane, F_x and F_y go to infinity, and the algorithm cannot produce reliable results. To overcome the problem, when the camera is approaching this condition, its orientation is arbitrarily set to (π, θ).

System Deployment

Deploying the indoor navigation system in a new location requires different steps. First, we create a digital map of the environment with CAD software, exploiting already available CAD files or bitmapped maps of the venues. Then, we define the initial position and orientation of each marker and the possible routes in the building. Finally, marker and path data are stored into a database and the 2D vector maps are post-processed, to define their final graphic look and/or their 3D extension, as required by the application.

When markers are physically deployed on site, we refine their location information, revise the marker list in case some of them cannot be placed as defined in the first step, and update the database accordingly. Any further change to the database, due for instance to unavailability over time of certain segment paths or to marker relocations, is managed by updating the application local data when they are found to be obsolete.

Routes are internally represented as a graph, where nodes are the turning points and edges are the path segments. The route between two points is computed with a shortest path algorithm. Besides user's location and target destination, the routing algorithm can take into account other contextual information. For instance, it considers the user preferences for stairs or elevator, the temporary availability of path segments (e.g., due to restricted opening hours of corridors, floors or venues), and the particular disabilities of the user, thus providing accessible routes for walking-impaired people.

4.3.5 Positioning from projected patterns

This class of systems retrieve positioning information by projecting structured patterns onto plans, such as walls or the ceilings, and can locate themselves with reference to that plan.

One of systems that pioneered this path was TrackSense [74]. The idea comes from the robotics world where researchers have explored several ways to autonomously locate robots in the environment without having to deploy additional infrastructure. Through laser techniques and ultrasonic range finders feature maps of the environment are built and used later to navigate the robot. This class of techniques is called This class of techniques is called Simultaneous Localization and Mapping (SLAM).

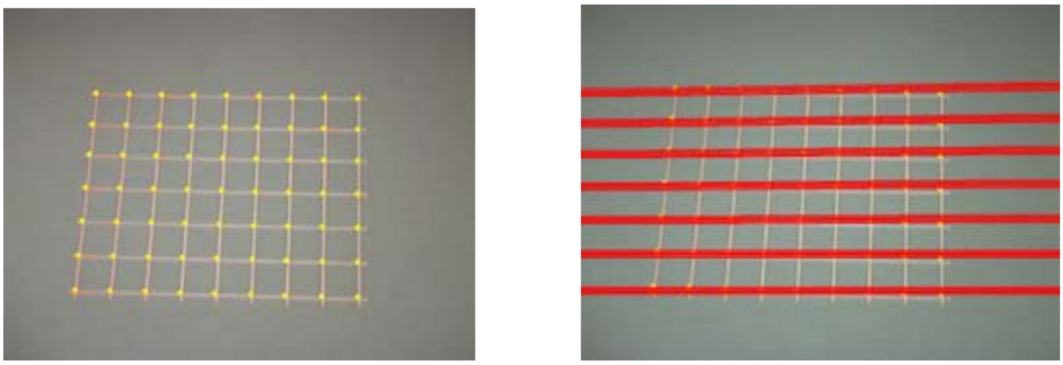


Figure 4.15: The TrackSense projected grid. Image from [74].

TrackSense was designed with the purpose of using vision based techniques only to retrieve the devices position with respect to a given surface. Images coming from the camera are analyzed in order to detect the grid lines. Once the lines have been detected, their intersection points are used through triangulation to determine the cameras location with respect to the projection plans.

4.4 Ultrasound based techniques

These category of techniques exploits the physical properties of sound, waves propagate at 343.2 meters per second at the temperature of 20° Celsius, to compute distances between emitting anchors and receiving sensors. Sound is a mechanical wave that uses the air as its propagation medium. In almost all the systems ultrasound frequencies are used as audible frequencies would result in annoyance for the users of such system.

Figure 4.16: The Bat transmitter. Image from http://www.cl.cam.ac.uk/research/dtg/attarchive/bat/.

Active Bat

The Bat System [146] uses 720 receivers to cover an area of around 1000 m^2 on three floors. A receiver is shown in figure 4.17. The system can determine the positions of up to 75 objects each second, accurate to around 3cm in three dimensions. Each Bat transmitter emits an ultrasonic pulse that is captured by the receivers deployed on the ceilings or on the walls of the rooms in the covered area. Furthermore each transmitter is linked to the fixed infrastructure by a bidirectional 433MHz radio link. As in the Acive Badge system all the information is processed in a central server. When the server needs to locate a Bat device it contacts the latter through the radio link and the Bat transmitter emits the ultrasonic pulse. The system knows which but was addressed and can process the information coming from the receivers that sensed the Bat device.

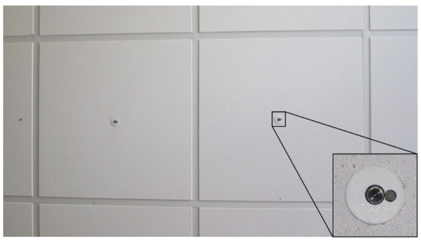


Figure 4.17: Ultrasonic receivers in ceiling tiles

By using three Bats on the same object, its orientation can be computed. The authors claim they can compute the orientation even with just one but by analyzing the pattern of receivers that detected ultrasonic signals from that transmitter, and the strength of signal they detected.

As with Active Badge the real issues with this system is the wiring and the deployment of the ultrasonic receivers.

Cricket

Priyantha in his PhD dissertation describes Cricket, an ultrasonic based location system [112]. Its functioning principle is similar to the Bat system with some peculiar differences. Cricket is based on a series of ceiling or wall-mounted beacons, like the one in figure 4.18 ,placed through a building publish information on an RF channel.

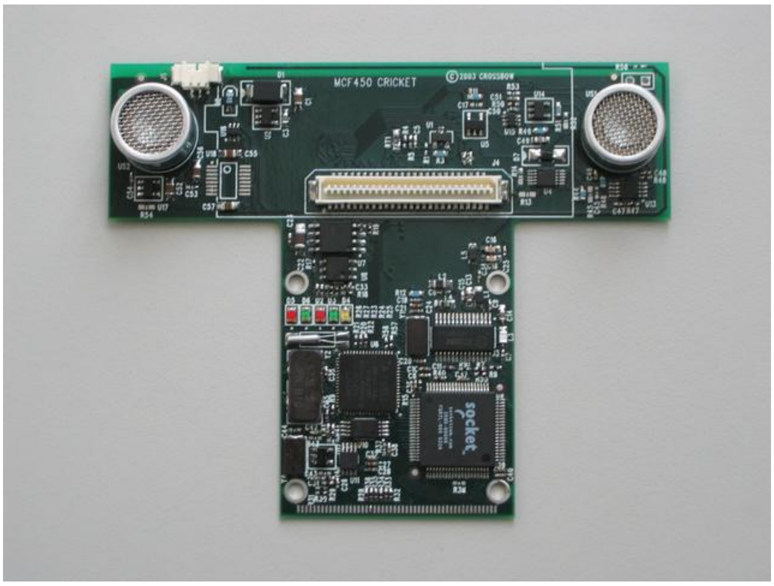


Figure 4.18: Cricket device, can act both as listener or a beacon. Image from `http://cricket.csail.mit.edu/`

With each RF advertisement, the beacon transmits a concurrent ultrasonic pulse. Listeners attached to devices and mobiles listen for RF signals, and upon receipt of the first few bits, listen for the corresponding ultrasonic pulse. When this pulse arrives, the listener obtains a distance estimate for the corresponding beacon by taking advantage of the difference in propagation speeds between RF (speed of light) and ultrasound (speed of sound).

Since RF velocity is much larger than the velocity of ultrasonic waves, when a listener receives an RF message from some beacon it starts listening for the ultrasonic pulse. This gives us the δT time interval between the two signals. This can be expressed as:

$$\delta T = \frac{d}{v_{us}} - \frac{d}{v_{rf}}$$

At normal room temperature and humidity, the speed of sound, $v_{us} \approx 344\frac{m}{s}$, and the speed of light, $v_{rf} \approx 3 \cdot 10^8 \frac{m}{s}$. Since $v_{rf} \gg v_{us}$,

$$d \approx \delta T \cdot v_{us}$$

The biggest difference with the Bat system is that Cricket nodes are able to perform anchor free localization by using mobile assisted topology generation techniques. The first step of this process uses RF connectivity to recreate the topology of the deployed nodes. Ultrasonic distance measurements are then used to fine tune the obtained model and to compute the beacon locations. The Cricket location system can achieve centimeter level accuracy with a maximum range of 10 meters.

Another notable ultrasonic systems is Dolphin, developed at the university of Tokyo [55]. Starting from few known anchor positions Dolphin can locate the other nodes through a recursive positioning algorithm.

4.5 Inertial techniques

Inertial positioning is achieved by integrating data coming from an inertial measurement units (IMU) composed generally of accelerometers and gyroscopes. Some also include magnetometers, which are used to overcome the orientation drift that affects almost all inertial techniques. In [59] Harle performs a thorough survey of available inertial positioning techniques. Measurement errors are present within the sensor data, and the triple integration results in potential cubic growth of this errors, drift.

Often called Pedestrian Dead-Reckoning (PDR) systems, these deal with human motion. By using IMUs it is possible do understand if a person is walking or running and the direction of the movement can also be determined as shown in figure 4.19.

These systems perform well overall but need other absolute positioning systems to be used together with PDR. Systems, like WiFi for example, could be used to address the drift faced by inertial methods.

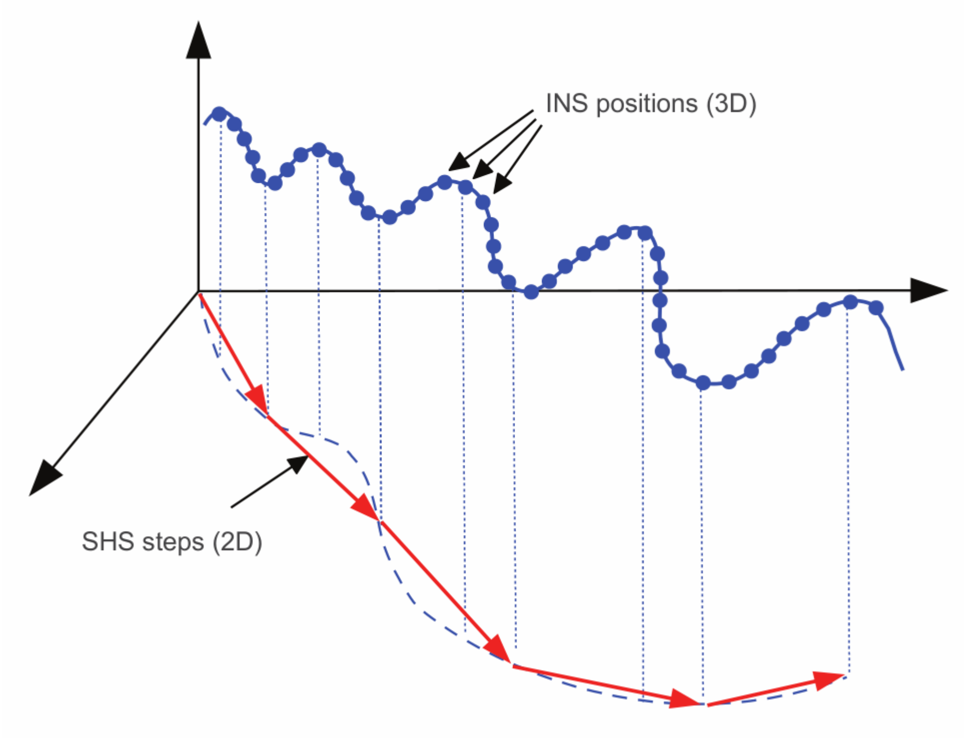


Figure 4.19: INS (Inertial Navigation system) and SHS (Step-and-heading system). An INS computes the full trajectory of a unit in 3D (solid line with position dots), whilst an SHS deals only with gross step vectors in 2D (arrow sequence). Image from [59].

4.6 Magnetic field based techniques

The Earth, because of the inner layers composition, acts as a big magnet and thus generates a magnetic field. The idea of using this magnetic field for positioning purposes arises from animals that determine their position from local anomalies in Earth's field. These fluctuations arise from natural and man made sources such as buildings, that contain metals in their structure, power systems and industrial devices. This anomalies can be exploited to determine the position of a device in indoor environments. Authors of [60] propose one the first solutions for indoor positioning. The achieved accuracy of almost 30 centimeters but the robot had to travel for 25m before on average in order to get localized by comparing the magnetic flux values. In [139] and [30] SLAM techniques are implemented with the purposes of locating robots in indoor environments.

These main disadvantage of magnetic positioning is the need for a magnetic fingerprints map of the environment.

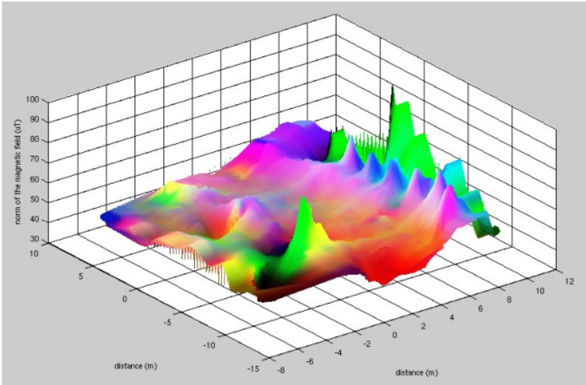


Figure 4.20: Magnetic landscape of University of Oulu Discus entrance hall.The height is the norm of the field and the color (red, green, blue) corresponds to its direction (x,y and z respectively). Image from [60].

4.7 Radio-wave techniques

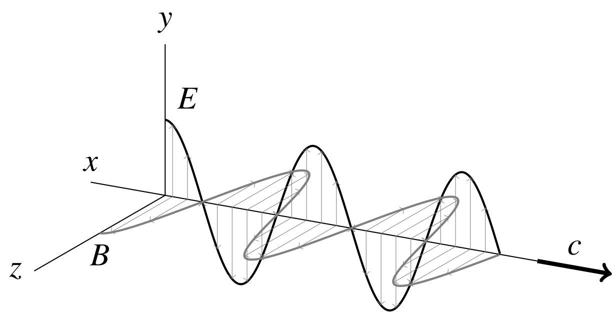
This section will cover those positioning systems that rely on wireless communication devices as they primary mean for obtaining positioning information. These are good candidate systems mainly because the necessary hardware infrastructure is already deployed for other purposes in almost all the indoor environment that could benefit from indoor positioning and navigation capabilities. Not only the infrastructure hardware is already there but as with inertial measurement units and camera hardware that are already available in modern smart phones and tablet personal computers, the same applies to networking hardware. Nowadays it is hard to find a mobile device that does not incorporate at least WiFi and Bluetooth radios, that basically are the same since WiFi b/g/n specifications and Bluetooth both operate in the unlicensed industrial,scientific and medical (ISM) band that ranges from 2.4 to 2.5 GHz.

Radio frequency based positioning methods do not exploit only the 2.4 GHz band technologies such as ZigBee [49, 68], Bluetooth[3, 54] and WiFi (standard IEEE 802.11) [8]. Indeed, the more precise results are obtained by using Ultra-Wideband (UWB) transceivers. Other scholars have proposed positioning systems based on the FM radio signals[26], radio frequency identification (RFID) technology and mixed radios such as WiFi and Bluetooth[9].

Before discussing the positioning systems based on radio communication technologies a brief description of the RF medium is needed. Understanding how the electromagnetic waves propagate from a transmitter to a receiver explains why some of these techniques have been employed and what issue is being addressed with every proposed solution.

4.7.1 Radio Frequency communications

RF communication is based on electromagnetic waves that propagate from a transmitter antenna through a medium, generally air, as depicted in figure 4.21. The communication message is encoded either through analogue modulation techniques (amplitude, frequency or phase modulation) or through more advanced methods such as direct sequence spread spectrum. Some variants of the latter are the foundation of our mobile communication networks.



E = electric field amplitude
B = magnetic field amplitude
c = speed of light (3×10^8m/s)

Figure 4.21: Electromagnetic wave.

Electromagnetic waves are transmitted with a certain signal strength, which corresponds to the transmitting power of the antenna. Traveling through air reduces the signal strength as described by the free space path loss formula :

$$P_L = \frac{P_t}{P_r} = \left(\frac{4\pi d}{\sqrt{G_L}\lambda}\right)^2$$

where G_L represents the product of the antenna gains and λ is the ratio between the speed of light and the frequency of transmission, the wavelength of that particular transmission:

$$G_L = G_t \cdot G_r, \lambda = \frac{c}{f_c}$$

Another equation relating the received power with distance and frequency is the Frii's Law which expresses how attenuation in free space increases with frequency:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

Given these formulas it would seem obvious that the distance of a transmitter from a receiver can be derived by simply applying the above equations. The above formula hold true when $d \gg d_f$, , and in line of sight scenarios, e.g. where there are no objects that obstruct the path from one radio to the other. This does not hold true in most of the time in indoor environments.

Another model for the path loss is the Log-normal one[129]. According to this model $PL(d)$ at distance d can be computed as:

$$PL(d) = PL(d_0) + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) + X_\sigma$$

if the path loss is known at distance d_0 (usually is equal to 1m). X_g instead is a Gaussian variable with zero mean that describes the random shadowing effect. Empirical studies show that the value of σ varies from 4dB to 13dB.

Wireless communications, especially in indoor locations suffer from a series of perturbations that make direct usage of transmission and reception power levels for range based purposes unreliable. The main causes of such unreliability are :

- Reflection: occurs when a propagating wave hits an object which has very large dimensions when compared to the wavelength of the former.
- Diffraction: occurs when the radio path between the transmitter and the receiver is obstructed by a surface that has sharp edges. When the wave hits these edges a set of secondary waves are generated and bent around the obstacle. The resulting waves depend on the geometry of the object as well as the amplitude, phase and polarization of the incident wave.
- Scattering: occurs when the wave impinges on a rough surface. The reflected energy is spread in all directions due to scattering.

The above phenomenons together are the causes of multipath propagation, a condition that is verified when radio signals reach the receiver antenna following multiple paths. The outcome can be constructive or destructive interference and phase shifting of the signal.

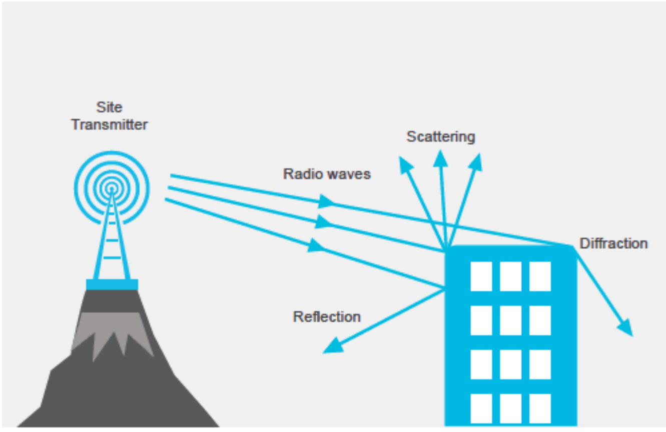


Figure 4.22: Reflection, diffraction and scattering. Image from http://goo.gl/ClUY7Q.

Evaluating the trajectories of RF propagation requires a very complex modeling of the environment. Ray-tracing techniques could be used[155] but it is still not enough and the computational effort needed to perform such analysis is really high. Furthermore antennas are not perfect and do not transmit with the same efficiency on all the directions as shown in figure 4.23. The radiation pattern is irregular and predicting how signal propagate from this antenna is an almost unfeasible task.

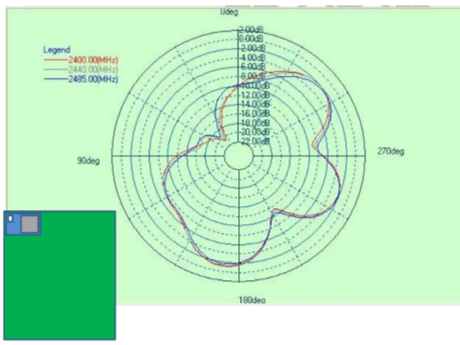


Figure 4.23: BLE 112A radio radiation pattern. Image from BLE112 documentation https://www.bluetooth.org/tpg/RefNotes/BLE112_Datasheet1.pdf.

These considerations lead to the conclusion that using the signal strength of a radio link as an indirect measure of distance is not possible. Still, radio technologies are amongst the most used solutions for indoor positioning by using the following principles:

1. Angle of arrival, AOA. Makes usage of specialized hardware to determine the angles of arrival of the radio signals.

2. Time of arrival, TOA, and time difference of arrival, TDOA. Used mainly with ultra wideband radios.

3. Fingerprinting. The environment is mapped by creating fingerprints of RF signals at certain locations. The biggest disadvantage is that the mapping process has to be repeated every time one of the anchors, whose signals are being fingerprinted, has to be replaced. A different organization of the furniture makes another session of mapping necessary.

4. Proximity. The sensors network is only able to tell whether the tracking device is near one of their nodes or not. The position of the device is supposed to be that of the sensor network node.

4.7.2 Angle of arrival techniques

Angle of arrival techniques use triangulation as their base principle. To determine the position of the device either the device is able to measure the direction from which the signals are coming for every station or, the system measures how the signals emitted from the device are being received by the nodes of the network. In the second case the networks of the system have to be precisely synchronized and all the processing is done on a central node that aggregates measured angles of the different anchors.

Ubicarse

Authors of [80] present Ubicarse, a patent pending technology that could enable handheld devices to emulate large antenna arrays using a new formulation of Synthetic Aperture Radar (SAR). SAR is used in aircrafts and satellites to map the topography of Earth's surface. It's primary goal is to allow a single antenna receiver to isolate and analyze the multiple signal paths emanating from a wireless transmitter. To achieve this the antenna is rotated while taking snapshots of the received signals. If combined this snapshots mimic a multi-antenna array and can generate a multi-path profile of the transmitter that can be further analyzed to determine the angle of at which lies the transmitter. SAR operations are limited to setups where the motion of the antenna is very precisely controlled.

Ubicarse uses two antennas attached to the mobile device. To precisely understand how this antennas are twisted Ubicarse uses the motion sensors of the device. This makes it possible to compute SAR on off the shelf devices without the need for very complex hardware, and being able to produce a multi-path profile for the detected access points as shown in figure 4.24.

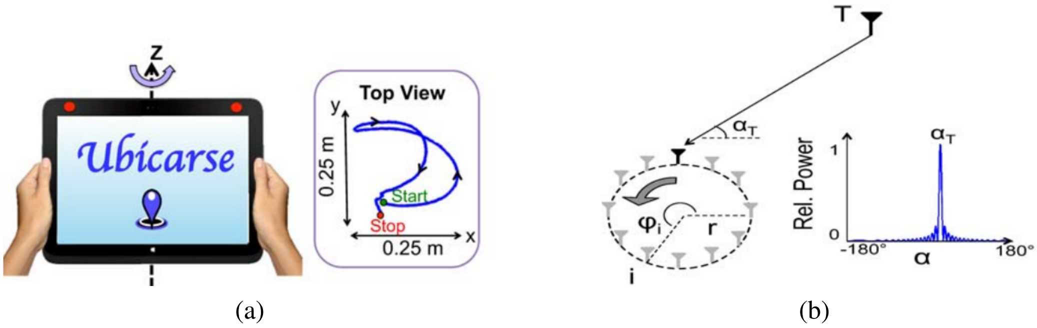


Figure 4.24: On the left is depicted the spatial movement of the mobile device. On the right it is shown how SAR is performed. Images from [80].

Ubicarse's core contribution is the ability to perform SAR on hand-held devices twisted by their users along unknown paths. Ubicarse is not limited to localizing RF devices; it combines RF localization with stereo-vision algorithms to localize common objects with no RF source attached to them. The system is capable of achieving very high precision accuracy of around 30cm without the need for special hardware, except for the antennas on the mobile device, and fingerprinting. Even in NLOS conditions Ubicarse achieves a precision of around 50cm. While very promising, Ubicarse still needs the user to perform a a particular action for the system to locate it. This situation is similar to the MusA one where the user has to point the marker with the camera to compute the location information. It still remains a very promising system as the it needs no additional infrastructure or fingerprinting to operate.

ArrayTrack

ArrayTrack[154] is an indoor localization system that exploits the increasing number of antennas of modern access points s to provide fine-grained location for mobile devices in indoor environments. When a client transmits a frame on the air, multiple ArrayTrack APs overhear the transmission, and each compute angle-of-arrival (AoA) information from the clients' incoming frame. Then, the system aggregates the APs' AoA data at a central backend server to estimate the client's location. While AoA techniques are already in wide use in radar and acoustics, the challenge in realizing these techniques indoors is the presence of strong multipath RF propagation in these environments.

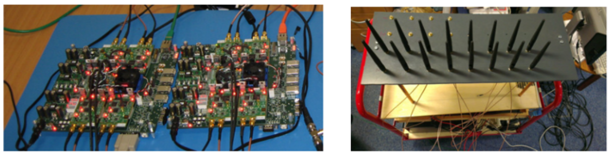


Figure 4.25: ArrayTrack access point FPGA and the antenna array. Image from [154].

ArrayTrack authors have designed a new multipath suppression algorithm to deal with the irregularities of indoor radio propagation. The system has been developed on special field programmable gate array circuits and has been evaluated in a 41 node network deployed over one floor. When a frame is detected the ArrayTrack AP quickly switches between sets of antennas to produce AoA information for every set. By combining this different received angles along different directions, given by the direction of the antennas, it is possible to compute accurately the direction at which the mobile device lies with respect to the network node. ArrayTrack is able to achieve 50cm location accuracy when a the device is in LOS scenario with nodes and a 1m accuracy otherwise.

4.7.3 Time Difference of Arrival

Distance from a transmitter to a receiver can be obtained if the time of flight of the signal, often referred to as time of arrival, is available. Computing the time difference is very difficult since the two radios have to be precisely synchronized. With electro-magnetic signals traveling at almost the speed of light even with 1 nanosecond of error in the measured time results in a 30cm error. Since this is very difficult to implement in practice, with the exception of UWB modules, another more suitable solution is to measure the round trip time for a packet or to employ time difference of arrival as the range-measuring principle.

The signal transmitted from the mobile device is received by two anchors on different times. The position of the mobile device lies on the hyperboloid defined by the two focis placed in the receivers locations satisfying $d(r_1, m) - d(r_2, m) = v(t_{m1} - t_{m2})$ where v is the speed of light, m is the position of the mobile transmitter and $r_{1,2}$ are the two fixed receivers. With three of these hyperboloids, e.g. with three receivers, we can compute the user's position by solving the obtained system [132].

Ubisense

TDOA and TOA techniques very precise and synchronized timings between the different receivers. Standard APs and mobile devices do not guarantee such strict parameters and as consequence special hardware is needed. Ultra wide band radios are used for these purposes as they can compute TOA timings very precisely by transmitting short bursts of signals over a large bandwidth, at least 500 MHz. This makes it possible to avoid multi-path effects and to very precisely determine the effective time of flight. If used together with TDOA it can achieve precision of 15cm with an operating range of 50 m. The most relevant system using UWB is Ubisense [6]. Ubisense works by creating sensor cells, each cell consisting of at least four readers. The operating band ranges from 6.5 GHz to 8 GHz. Mobile tags are located by means of TOA and TDOA and the cells can be networked together. The readers receive data from the tags transmit it to the Ubisense Smart Space software platform.

UWB is a very good solution for indoor positioning but its high cost of available solutions, make the technology affordable by few.

4.7.4 Fingerprinting - RSSI

RF fingerprinting falls under the scene analysis class of indoor positioning technologies. It's main drawback is the calibration phase that has to be carried out before the system could operate. The calibration is done by fingerprinting RF signals in different locations and possibly even in different time periods. In [26] FM signals have been used for fingerprinting based indoor positioning.

Once the database is built, the obtained radio map is used to estimate the users location at a certain time. The performance of these category of systems can reach meter-accuracy, depending on the number of the stations and the density of the calibration points. Probabilistic methods, support vector machines, neural networks and k-nearest neighbors are amongst the most used methods for correlating the current fingerprints vector with the radio map.

To avoid the off-line radio map building session several systems have been proposed. Some of them collect the fingerprints passively while users carry one their daily operations [28]. In the EZ system, these fingerprints are collected by a central server that uses genetic

[6] UbiSense. `http://www.ubisense.net`

algorithms to determine the position of that fingerprint based on propagation models of the antennas and to better refine the same models.

Radar[8] and Horus[157] represent two of the most notable WiFi fingerprinting indoor positioning solutions. Horus manages to achieve very high accuracy but to do this it needs to perform a very intensive off-line stage that consists in the collection of the fingerprints. These sessions are carried out by different persons in different times and the resulting datasets are processed to produce a radio-map of the environment that considers even small scale variations of the RSSI values. With Radar, the authors covered a 1000 square meters of area with just 3 access points ant obtained a position of 2-3 m. Horus instead manages to achieve 60 cm accuracy.

As stated before the main disadvantage of fingerprinting based techniques is the calibration stage.

Dynamic radio-maps and zero-configuration systems

In [81] authors use fingerprinting in the off-line stage and then update the kernel estimator by taking into account RSSI volatility in the on-line step. The achieved accuracy is in the 3m range. In [86] authors propose a zero configuration system where the main effort is put in the characterization of the relation RSSI-distance from the receiver, although they use fingerprinting between two co-located anchor nodes to estimate the self-RSSI of the system. The position estimate is than computed by using lateration, given the computed distances from the transmitters. In Chapter 5 I propose a different approach without using any lateration or angulation, indeed no distances are computed between the mobile device and the anchor nodes. In [6] authors build the radio-maps without any fingerprinting by deploying wireless monitors next to each IEEE 802.11 WLAN wireless router. The accuracy of the positioning system is in the 2 - 3m range.

Bolligher presents with RedPin[17] a collaborative indoor positioning system where the mobile device measures the strength of signals received from nearby WiFi access points or GSM cells as well as identification details about any Bluetooth device in the surroundings. This information is forwarded to a central server that searches for matches of those values in its database and sends back to the mobile device its most plausible location. When the server can not retrieve the measured values in its database the application on the mobile device asks the user to specify its location by selecting the appropriate map and by pinning her/his current location. This system would result very interesting in a scenario familiar to the users, who continuously return in the environment to refine the indoor positioning system's accuracy. It is not the case of a cultural venue.

4.7.5 Proximity

Proximity algorithms provide symbolic relative location information. They rely upon a dense set of networks deployed in the environment. When a mobile target is detected by a single antenna, it is considered to be collocated with it. This method is relatively simple to implement and generally infrared radiation (IR) and radio frequency identification (RFID) technologies are used for such positioning systems. Other more recent implementations use Bluetooth Low Energy. The proximity profile, defined in the BLE standard, was designed for this purpose and it is used in the iBeacon implementation by Apple and by Google's Eddystone protocol.

Proximity positioning presents the major drawback of needing a very dense and large network of nodes to cover all the environment. Location information can be achieved only at the covered locations. Placing beacons everywhere makes deployment and maintenance costs rise and make this systems suitable for very coarse-grained location needs.

Chapter 5

Proposed solution

The previous chapters introduced the motivations for using a positioning system. The integration of this kind of system in the museum experience is necessary not only for navigation purposes. Indeed, this can be seen as a side benefit. As stated in chapter 2, knowing where the visitor is while she/he is doing something gives meaning to that action. Putting together a series of actions can lead to understanding how the visitor fits in the proposed models and this can lead to an almost tailor-fit experience as the digital tool becomes a true guide that "understands" who you are and what are your actual needs and interests.

Without a positioning system one of the most important contextual information in a museum is not available and this limits greatly the ways in which this digital guides can adapt to the visitor. The MusA framework comes with an optical indoor positioning system that while very accurate for determining the user location presents two main issues when trying to understand the visitors behavior:

- The location system needs the user to point at one of the markers as its input. This is kind of a burden for the visitor and also an issue for the system. As Weiser said in [149] "The most profound technologies are those that disappear...". A disappearing technology is invisible and does not need our help to be useful. The common expression "it just works" should be seen as goal for these systems. Less user intervention means less issues as the designer do not have to worry about one more possible interaction. It also would make the users experience less focused on how to point a marker and more involved in the actual museum experience.

- The location system is exploited only and every time the user points one of the

> markers. It means that for the rest of time the system has no idea at all of where the user might be. This limits the possible analysis that can be carried on. Visitors behavior analysis can not be considered accurate if we have only information about locations in certain moments in time. The only way we have to relate this action is to use time, but it is not enough. If at a certain moment the visitor pointed a marker on the first floor and then 15 minutes later he pointed another on the second floor it is impossible to know what she/he did in that period of time. One of the main problems in conveying suitable guidance to a user in a museum, is information overload. If the user is exposed to too much content, his capability to understand it quickly drops and information turns into noise. The lack of knowledge of what happened between two consecutive marker readings, prevents the system to make a reasonable guess about user behavior (did he stop and set somewhere? did he visit another wing of the museum? did he exit and come back again?) in order to properly select the level of detail to present him in further interactions.

Other scholars have addressed the topic of tracking users behavior by using both intrusive and obtrusive means. A notable example of the first is the work carried on by Cucchiara and Del Bimbo [35]. They propose either computer vision based solutions or smart floors that detect visitors presence and react accordingly. The computer vision solutions instead are of two kinds:

- Envi-vision solutions: this systems include traditional vision systems for video surveillance, in a single or networked configuration, as well as new sensing devices such as multisensored surfaces.
- Ego-vision systems include solutions that utilize wearable cameras and mobile cameras in handheld devices.

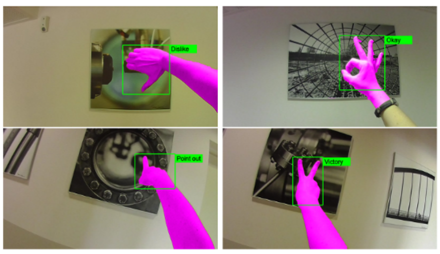


Figure 5.1: Examples of visitor interaction. Image from [127].

The envi-vision systems are used to track and profile visitors behavior. They employ computer vision techniques to track single visitors or groups of visitors for better understanding their interaction with the artworks on display. Although promising, this kind of solution in my opinion presents a major drawback. A single visitors path is difficult to reconstruct and analyze as the required computing power to deal with hundreds of visitors, some of them will even look alike, is huge. To overcome this issue authors propose also sensing floors that could be used to count people, monitor their pauses, and profile their degree of attention. But still matching this data together is not a trivial task. The ego-vision approach on the other hand employs wearable cameras to detect users' interaction with the artworks on display [127] as shown in figure 5.1. This approach presents again the same issue as the MusA marker pointing system. User understanding and usage of the system is of paramount importance. If the visitor perceives this interaction as difficult and not immediate he will not use them and the tracking system will not be exploited properly.

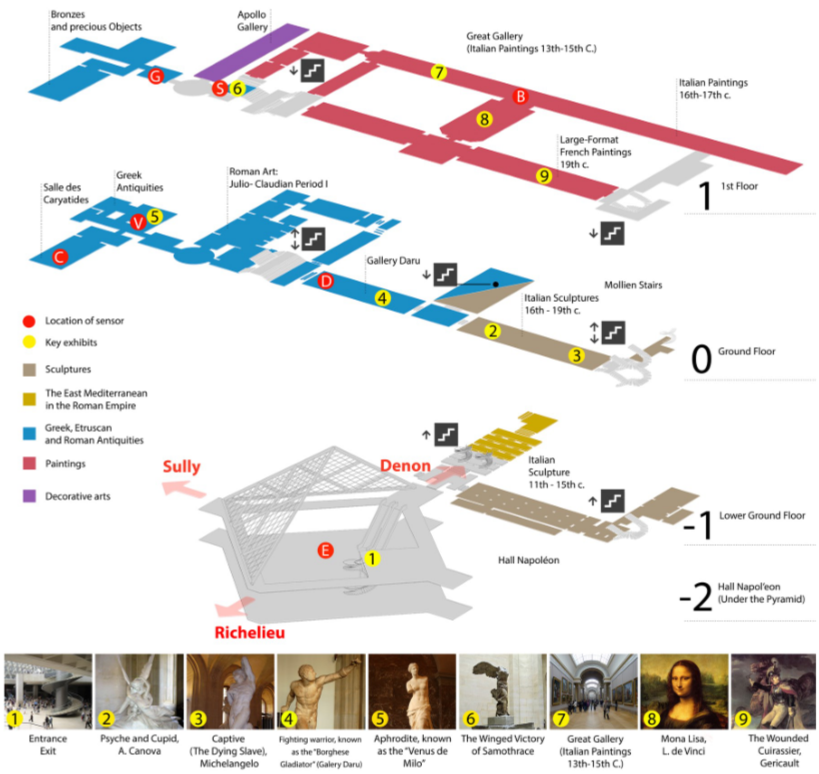


Figure 5.2: Bluetooth beacons deployed in the Louvre Museum. Image from [156].

Another possible way of tracking visitors behavior in an unobtrusive way has been designed and implemented by Yoshimura [156] in the Louvre Museum. Seven Bluetooth sensors have been deployed in some areas of the museum for unobtrusive observations of the visitors movements inside the halls as shown in figure 5.2. Once a Bluetooth-activated mobile device enters a detection area, the sensor receives the signal emitted by the mobile device and the detection continues until the device leaves the area. Data was collected for almost 30 days. The authors report an average of 8.2% of the visitors activating the Bluetooth connection on their handheld devices. Authors assert that many features of the behavior of the long-stay and shor-stay visitors, including the path sequence length and the unique nodes visited, do not appear to be strikingly different between visits of different duration, and are sometimes even independent or nearly independent of duration. This could be an outcome of the usage of only 7 nodes in all the venue.

This latter approach to visitors behavior analysis exploits a proximity technique for the positioning issue. The authors chose Bluetooth connectivity over RFID. With this choice authors do not need to give every visitor special hardware as almost any mobile device nowadays has such radios. Even this system, in my opinion, can not be applied for understanding a single visitor's behavior and providing her/him with a truly personalized experience.

How can we solve these issues? A possible solution could be a tracking system that works silently in background and that understands where the user is and what he/she is facing. This system has to satisfy some requirements determined by the venues where it will be deployed.

Museum venues requirements

Cultural venues such as museums are peculiar environments. Their internal organization, in terms of panels and furniture, is rearranged to adapt to new expositions. Deploying new hardware in these environments is challenging since the physical space is intended for artworks and exhibits and not for complex hardware installments. Deploying a system like Active Bat in a museum would result in enormous amount of work and very high maintenance cost. Every time a temporary wall is rearranged, these changes have to be considered and the positioning system must be updated. Another limiting factor for cultural venues is their budget, especially here in Italy. Often they do not have enough spare funds to pay and maintain complex hardware systems. The above considerations lead me to the following requirements that a candidate indoor positioning system must satisfy in order for it to be considered as a plausible solution.

- Low cost (operational, investment). The initial investment and the maintenance cost must be as low as possible. This means that fingerprinting approaches are to be avoided, where a new database has to be rebuilt every time the environment changes (multi-path effects in indoor environments change with changes in the space organization).

- Self healing (ability to react to environmental changes). This feature is related to the previous one. If a fingerprinting session is to be avoided every time there are changes then either the system employs technologies such as 4.7.2 or its nodes should detect these changes and properly update their reference models.

- Low environmental impact. In museums it is difficult to have outlets everywhere in the environment. Placing WiFi access points in locations strategic to the positioning algorithm is complicated. The topology of network nodes impacts severely on the performance of an indoor positioning system.

- Coarse-grained precision ($2 - 3m$ accuracy). In a museum venue we do not need very high positioning accuracy. We are not dealing with an industrial plant where precision is needed for the machines to operate precisely and safely. The coarse-grained precision is also dictated by the technique used for indoor positioning. Ultra-wide band modules are very precise but they overall cost is high, so to keep the system cost low we must employ less precise solutions.

- Compatible with standard consumer devices. This requirement is important for two reasons. Visitors are already familiar with their own devices and nowadays almost every one possesses a smartphone. This means that for the museum there is no additional hardware to maintain and for the visitor there is no need to get familiar, manage and carry on one more device.

With these requirements in mind I will now discuss the proposed solution for the indoor positioning task.

5.1 System architecture

The requirements highlighted in the previous section and the study of the available indoor positioning technologies lead to the choice of Bluetooth Low Energy, BLE, as a candidate technology for the sensor network to be deployed in this new positioning system. Several commercial solutions already exist that offer indoor positioning capabilities but the system details and implementation for most of them are not available. Some notable examples of such solutions are:

- Estimote beacons: can act both as iBeacons for the Apple platform or EddyStone beacons, a standard defined by Google. The working principle is proximity [1].

- Indoo.rs offer proximity services and also indoor navigation at the San Francisco Airport [2]

- Nextome[3] is an italian based company that claims indoor positioning accuracy of up to 0.5m although in the indoor positioning competition, ISPN 2014, held by Microsoft, they managed to achieve 2.72m of accuracy[4].

The literature offers several studies and approaches for BLE based positioning. In [50] the authors have tested BLE with a fingerprinting approach and their conclusion is that even though precision is not high (accuracy around 3m) BLE is still a good candidate solution due to its low costs and relatively small fingerprint. In [160] authors suggest that BLuetooth Low Energy might be more accurate for location based services highlighting also other advantages of BLE over WiFi (low power, unobtrusiveness, higher scan rates). An approach, based on fingerprinting has been proposed in [161]. The authors have trained the system with 12000 RSSI captures and use the training results to estimate the location of the mobile device. This approach presents the same issue as all fingerprinting solutions. Every time something changes in the environment a new training has to be carried on. And this would result in an increase in the maintenance costs of the system. Authors of [93] propose an indoor positioning solution where the mobile devices estimates a distance from each sensed anchors where a is a pre-calibrated exponential decay term for the RSSI evolution. This estimates are reported at fixed time intervals to a central server. It processes all the incoming distances by and computes the filtered position estimates with a reported accuracy of 0.53 meters in a 9x10 m^2 laboratory.

[1]Estimote reference : http://estimote.com/

[2]Indoo.rs website : http;//indoo.rs

[3]Nextome's website http://www.nextome.net/

[4]ISPN 2014 results: http://research.microsoft.com/en-us/events/ipsn2014indoorlocalizatinocompetition/

To avoid fingerprinting the radio-map of the BLE propagation model must be constructed in a dynamic way. This means that the path-loss of the bluetooth signals has to be estimated and with BLE devices this can be carried on in a relatively simple way. BLE anchors sense each other from time to time and report the sensed nodes in their advertisement payloads. This behavior is useful also for detecting changes in the environment. Indeed the latter would result in the nodes sensing each other differently. The self-healing requirement is also satisfied if we build the radio-map in such a way. The next section will give an overview of BLE.

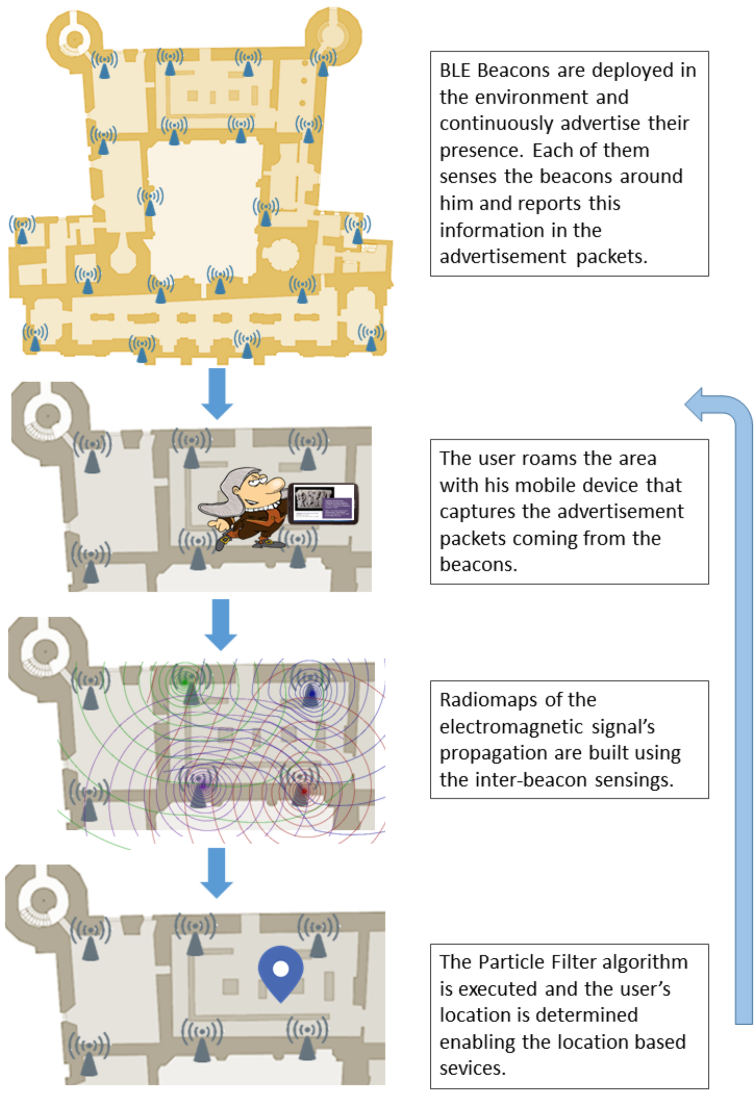


Figure 5.3: Schema of the proposed solution.

5.2 Bluetooth Low Energy

Bluetooth Low Energy is a radio communication standard defined by the Bluetooth special interests group. It is commercially labeled as Bluetooth 4.0 (now the standard has reached version 4.2). BLE is intended to be used in small, low energy, low power devices such as wearables, health monitoring sensors and every possible application where low energy consumption is a necessary requirement.

BLE operates in the ISM 2.4GHz band. The available bandwidth is divided into 40 channels, 3 of which are dedicated to advertising capabilities as shown in figure 5.4. While in a communication BLE devices perform a frequency hopping to avoid possible interference from other wireless devices.

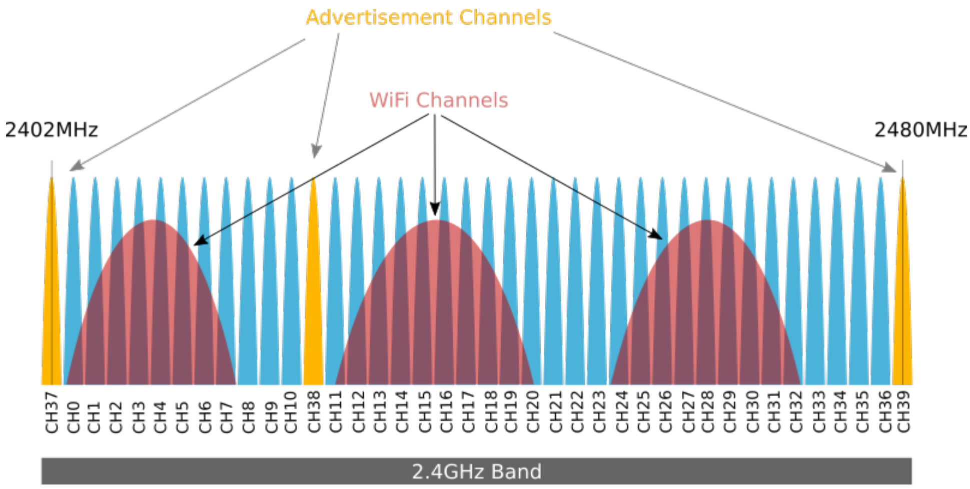


Figure 5.4: Bluetooth Low Energy channels.

The advertising channels are placed in non adjacent frequencies of the spectrum to avoid interference. Advertising devices are called slaves or servers. Usually they advertise a series of services composed of characteristics that can be read or written. Devices that scan and connect to these servers are called masters. After a successful connection masters can start discovering the slaves services and characteristics.

In my solution I will not use BLE in this classic way as I want the communication with these devices to be as fast as possible. How can the radio map be shared among the nodes then? This can be achieved by using one of the two scanning modes offered by the standard:

- Passive scanning is usually performed when devices need to know what peripherals are in the surroundings. This mode uses only one packet emitted by the slave during the advertising windows.

- Active scanning uses two communication frames, one to advertise its presence and the other one as a response to a scan request performed by a master who is scanning actively.

The scan response frame can contain up to 31 bytes of user payload data that together with the 29 available in the normal advertising frame makes for 60 bytes of data. This size might seem very limiting but it is enough to hold information about 30 nodes if their addresses are shared between the nodes in the form of an array. This means indexes and a byte for the sensed beacon RSSI are needed for every nearby node.

Having no communication makes the battery life of such devices very long. If set to advertise with a frequency of 10Hz a beacon can last a month with a single CR2032 3V battery. Bigger batteries could be used to ensure a longer operational time and lower the maintenance costs. The first prototypes of the BLE nodes were programmed to advertise at a 0.25Hz frequency in order to make the these nodes last for almost 2 years with a single CR2032 battery. This choice resulted in very poor positioning accuracy as the indoor positioning algorithm needs to measure at a much higher frequency. At the moment the BLE nodes are programmed to advertise with a 10 Hz frequency.

5.2.1 BLE112 devices and the customized firmware

Once the sensor network technology was chosen we had to find BLE chips. The main requirement was that their firmware could be customized in order to implement the node sensing algorithm. We chose the BLE112 devices from Bluegiga. Their reduced form factor and the possibility to easily modify their firmware were the main reasons behind this choice.

Figure 5.5 shows the first version of the network nodes. The comparison the BLE module with the housing of the 3V CR2032 battery shows just how small this devices are. Measuring only 18.10 mm by 12.05 mm these devices can fit very easily in small housings where the size depends on the batteries more then the chips.

This first version had a major problem, discovered later when implementing the positioning algorithm. The ceramic antenna of the chip was placed too closely to the battery housing and this resulted in very unreliable communications with the device. The received

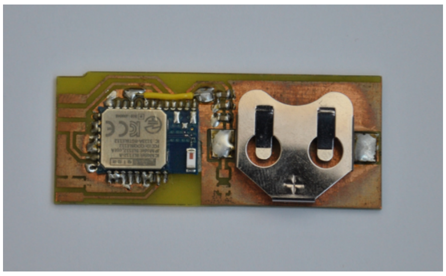


Figure 5.5: First version of the network nodes.

signal strength indicator fluctuations were very high because signals emitted from the antenna were propagating in paths determined by how they hit the battery metallic frame. This lead to a second version of the nodes as shown in figure 5.6.

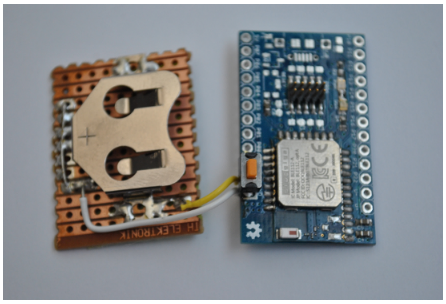


Figure 5.6: Second version of the network nodes.

Radio Frequency characterization

Once the hardware was complete, an RF characterization experiment was conducted to understand how these nodes would sense each other and how they are sensed by a mobile device, a LG Nexus 5 Android smartphone.

Two nodes and the smartphone were placed in the corners of an equilateral triangle with 1 meter sides. A custom Android application was developed to record all the sensed values between the nodes and how the phone was sensing these devices. The results of the experiment are shown in figure 5.7. The horizontal axis represents the values of the received signal strength indicator ranging from -40 to -80. The blue bars represent the distribution of the RSSI value sensed by the smartphone, based on 800 samples.

It appears clear that the mobile device has large fluctuations even in line of sight and at the distance of 1m. It senses the two nodes with almost 20 dB of span. Surely, the three devices were interfering with each other and the phone is the more disadvantaged one as

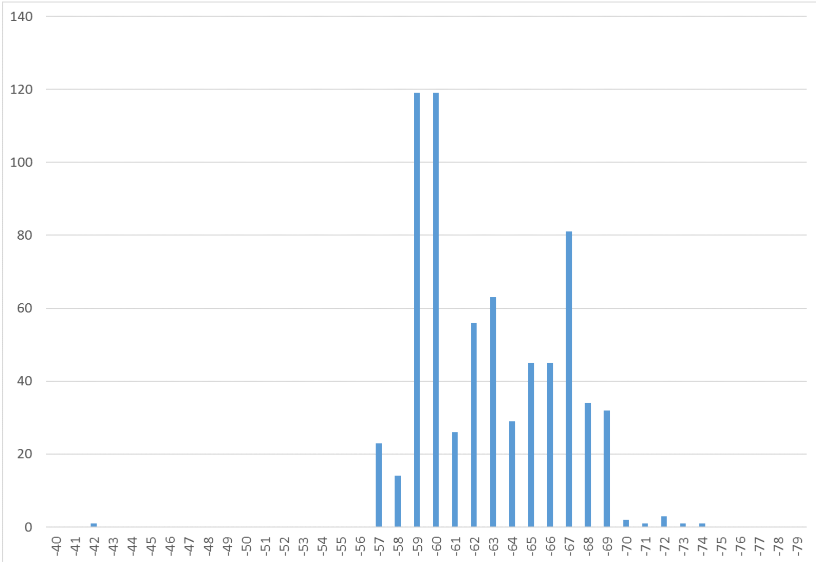


Figure 5.7: RSSI values distribution as sensed by the mobile devices placed at one meter from both anchors.

its radio antenna is not exposed as the one present in the BLE112 modules. But, since we want to rely on the phone's sensing capability we must employ a mathematical tool that can deal with these kinds of fluctuations in measured data. My current approach is to use a time series of the sensed beacon information. The more recent values are weighted the most while the older ones contribute less to the final reported RSSI value as shown in figure 5.8.

Another issue to be addressed is how to build the radio-map of the BLE node propagation model. To do this we use the fact that every anchor is sensed by surrounding ones. These neighbor nodes, if enough dense and well distributed contribute to the generation of the radio-map.

Radio-map generation

The ideal propagation model of an antenna can be modeled as a sequence of circles that are all centered in the antenna and each one of them represents a different power level of that particular node. As we go farther from the antenna these power levels decrease. These contour lines express how receivers placed at that distance from a transmitter sense the latter.

The antennas we are dealing with are not perfect isotropic antennas. This means that the corresponding contour lines, representing the power decay, are not circles. As seen in

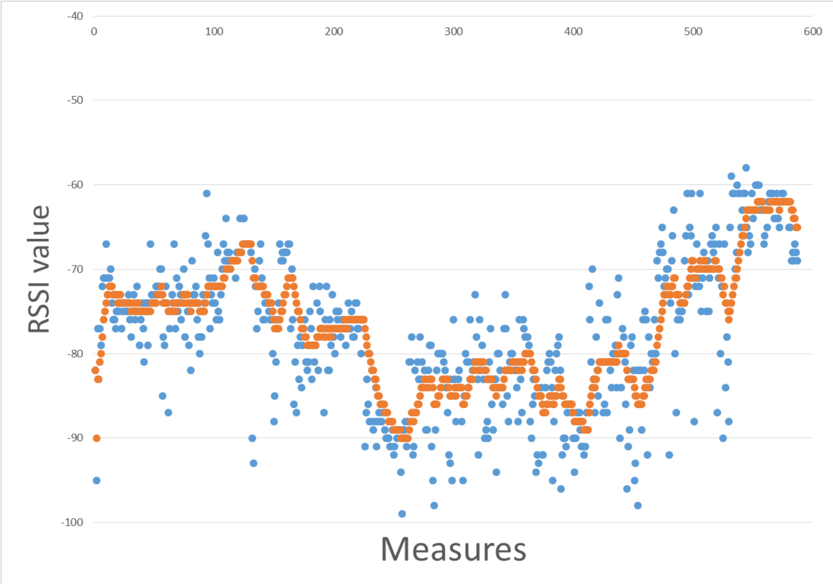


Figure 5.8: The blue dotted series represents the incoming RSSI measurements for the node. The orange series represents the RSSI filtered value.

4.7.1 these lines are not even continuous. Certain areas of the environment will behave like islands having their own power levels.

Since we have no fingerprints to generate these models and predicting the multi-path effects of antenna propagation is almost impossible I choose to approximate the actual distribution of power using the available information: the signal coming from a given device is sensed along different directions by its near-by nodes, with a given power level as shown in figure 5.10. For each reported value, we interpolate, along the corresponding direction, the power level at different distances, using the power loss model formula:

$$PL(d_{ac}) = PL(d_0) + 10 \cdot n_{ac} \cdot \log\left(\frac{d_{ac}}{d_0}\right)$$

Considering that $PL(d_0)$ and d_{ac} are given, with $d_0 = 1m$ we can retrieve n simply:

$$n_{ac} = \frac{PL(d_{ac}) - PL(d_0)}{10 \cdot \log\left(\frac{d_{ac}}{d_0}\right)}$$

We thus assume that the signal is strictly monotonic w.r.t. distance; moreover we assume that power level is spatially continuous. In order to reconstruct a possible signal distribution along all the un-sensed directions, we connect all points labelled with the same power level along the sensed distances with Catmull-Rom closed splines, in order

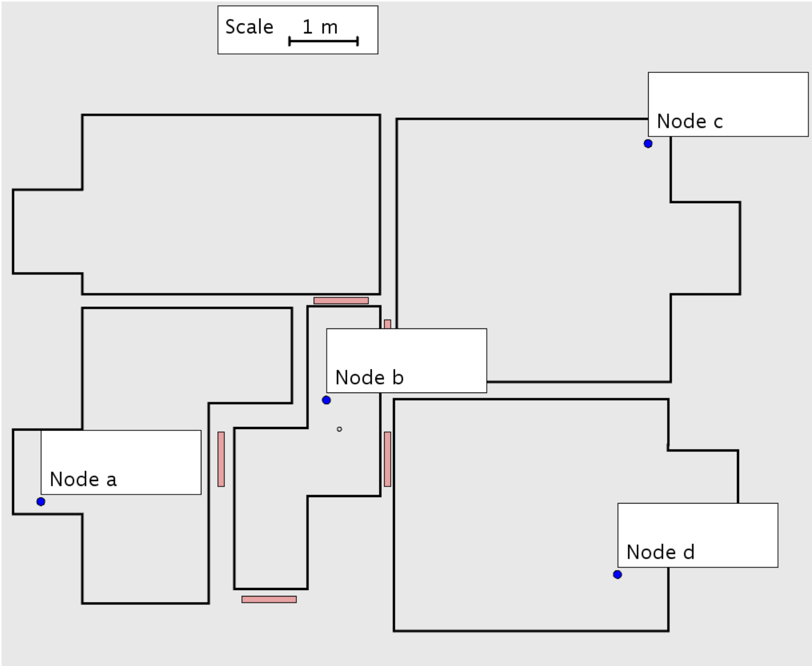


Figure 5.9: The initial state of the radio-map generation. The mobile device has not captured any advertising packet from the nodes. The only known informations are the nodes' locations.

to depict the curves where the signal hypothetically assumes the same power level. The choice of using the Catmull-Rom algorithm is clearly arbitrary, but is driven by the need of getting a curve which is continuous in its first few derivatives and is, at the same time, easy to compute from the available data. The outcome of this process is presented visually in figure 5.11.

After this step is repeated for each node that senses the current one we have a set of couples (n_{dir}, dir) where dir represents the direction in terms of orientation if the current node, i.e. **b** for example, is the center of its two dimensional world.

Since this kind of radio maps are derived algorithmically from sensed data, they can be expressed in a very terse representation, simply reporting the sensor identity and the received power level of each near-by node. This information can be broadcasted periodically by each sensor, exploiting BLE advertising packets. A mobile device roaming in a given area can collect all advertising packets and use the contained information to build its own dynamic copy of the radio-map, provided that it knows the actual position of BLE sensor nodes (which is reasonably a configuration piece of information that can be stored in some public server, the address of which can be optionally be stored in some

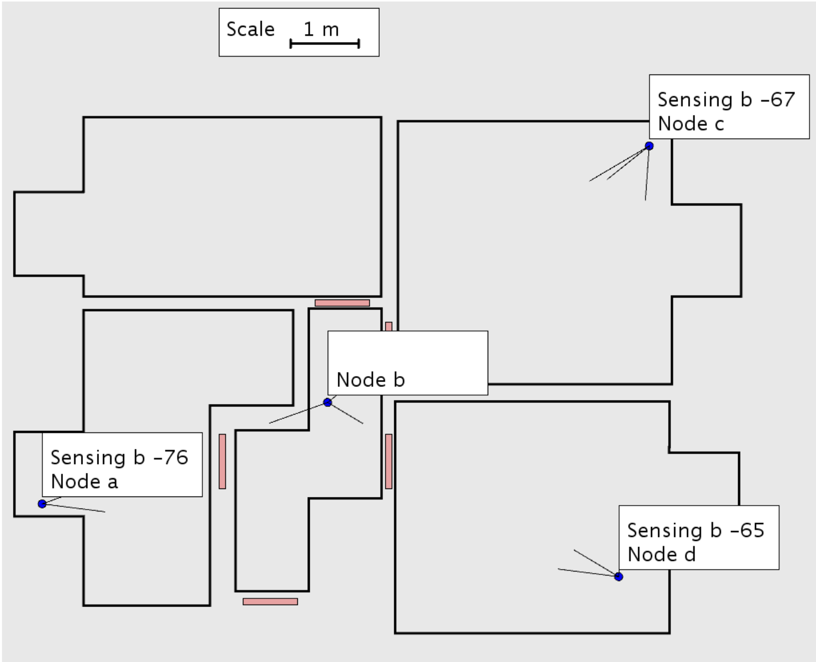


Figure 5.10: Nodes **a**, **c** and **d** report how they sense Node **b**. Directions between nodes are known.

extra property of the BLE nodes).

Once all radio-maps are constructed we have a set of k layers, one for every node that is being sensed in the area. If we imagine looking down on our two dimensional world with these layers, each centered on its node, we should see something like figure 5.12. Every point in this space can be represented not only by its coordinates (x, y) but also by a $k - tuple$ composed of the k power levels of each layer at that point in space. The set of all these tuples represents the radio-map of our environment. It is a discrete distribution because not all the possible combinations of the different power levels of the devices are represented and it is also the most we can get out of the inter-node measurements. But it makes it possible to avoid fingerprinting of all the environment. If any changes happen in the area, i.e. some panels are rearranged for a new exhibition, the inter-node measures will be updated together with the tuples distribution after the next phase of node sensing.

The radio-map represents our belief function that for every set of (x, y) coordinates returns a tuple that most likely represents how the mobile device should sense the anchors at that point in the two dimensional space. The positioning problem could be solved by searching through all these tuples looking for the ones that resemble the most to the current mobile device sensed values. While roaming in the environment a BLE active scan

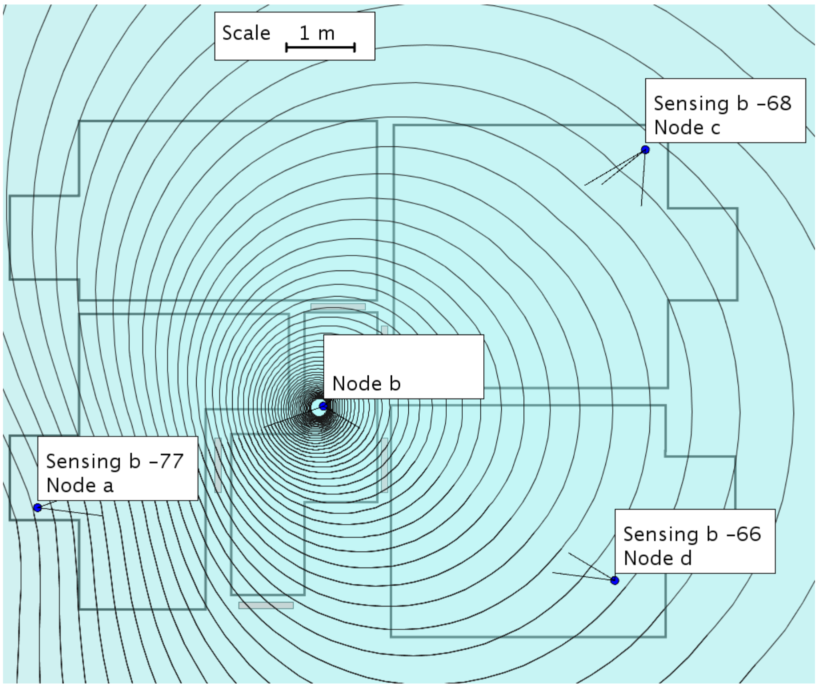


Figure 5.11: The antenna radiation radio-map of node **b** generated by knowing how that node is sensed by other surrounding nodes.

is performed continuously to intercept all the advertising packets coming from the BLE nodes. For every one of these captures we are able to retrieve the payload data containing the partial radio-map data and also an RSSI value describing the received signal strength for that node. The comparison of the radio-map tuple with the one representing the current sensing of the mobile device can be carried on by means of Euclidean Distance. For an n-dimensional space this can be expressed as :

$$d(p,q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + \ldots + (p_i - q_i)^2 + \ldots + (p_n - q_n)^2}$$

The Euclidean Distance represents the length of the vector $\vec{d} = \vec{p} - \vec{q}$. Since we are just interested in how far this two measures are we consider just the distance and no direction. Since there is a lot of variance even when two devices are in static positions we should not use the absolute distance but smooth it with a function that takes into account the RSSI variance and returns a weight $w \in [0{,}1]$. The weighting function and the grade of similarity between the radio-map distribution and the real propagation distribution are fundamental for accurately finding the user's location.

Once all distances are computed the positioning problem can be seen as classification

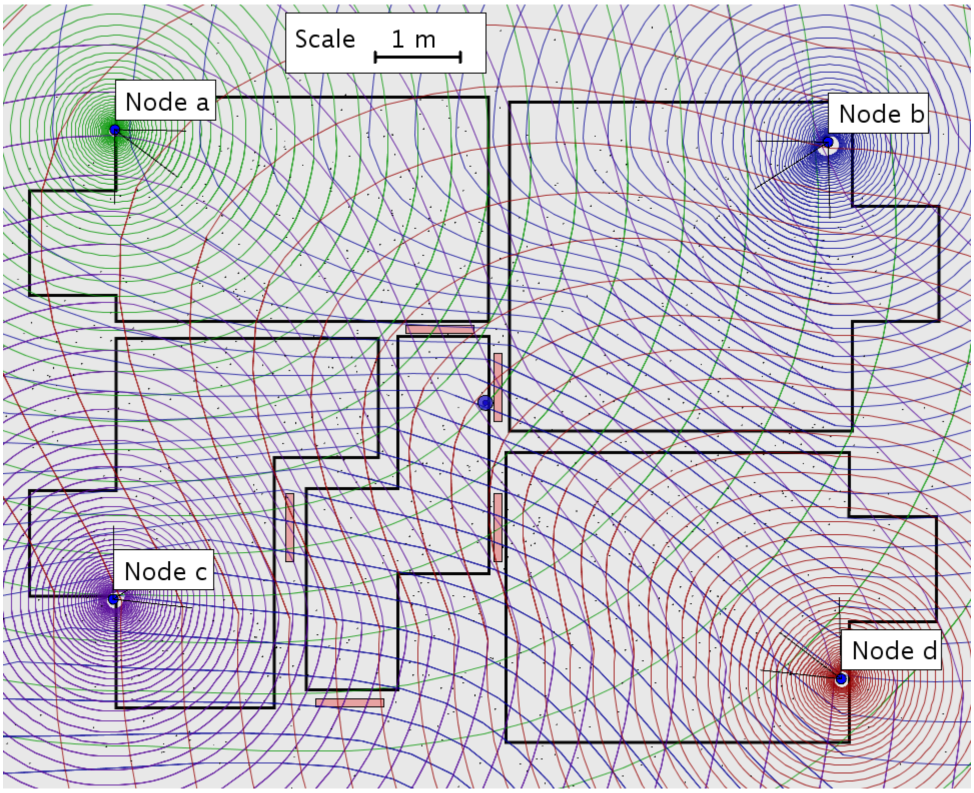


Figure 5.12: The radio-maps of the four nodes.

one. We have NxM candidate locations and for each we have also a distance from the current signal strength vector. A decision rule is to choose a subset of locations that have minimal distances from the signal strength vector.

5.3 Solving the positioning problem - Particle filters

To overcome the computational effort of analyzing all the set of locations every time there is a new sensing in input, I chose to use a Bayesian approach and implemented a Particle Filter. Particle filters are well suited for tracking purposes especially if the incoming measures do not come from Gaussian distributions [116]. These filters are more performing than the Kalman Filter when the system we are dealing with is not linear. A simple, yet effective introduction on Particle Filters can be found in [104].

Bayesian estimation is particularly suited for performing inference in state-space models where the state of a system evolves in time and information about the same is obtained by means of noisy measurements [104]. The evolution of system's state can be described by the equation:

$$x_i = f_i(x_{i-1}, v_{i-1}) \tag{5.1}$$

where x_i represents the state of the system at time i, v_{i-1} is the state noise vector and f_i is a time dependent function describing the evolution of the state vector. To estimate the current state we must take into account all the measures up to time i, denoted $z_{1:i}$. This means computing the distribution $p(x_i|z_{1:i})$, which can be done recursively in two steps. In prediction step, $p(x_i|z_{1:i-1})$ is computed from the filtering distribution $p(x_{i-1}|z_{1:i-1})$ at time $i-1$:

$$p(x_i|z_{1:i-1}) = \int p(x_i|x_{i-1})p(x_{i-1}|z_{1:i-1})dx_{i-1} \tag{5.2}$$

In the above formula $p(x_{i-1}|z_{1:i-1})$ is known by recursion and $p(x_i|x_{i-1})$ is obtained from equation 5.1. The distribution $p(x_i|z_{1:i-1})$ is the prior over x_i, before receiving the measures z_i. In the update step, this prior is updated with the latest measurements using the Bayes' rule to obtain the posterior over x_i:

$$p(x_i|z_{1:i}) \propto p(z_i|x_i)p(x_i|z_{1:i-1}) \tag{5.3}$$

The computations in the prediction and update steps cannot always be carried out analytically, which leads to the approximate methods such as Monte Carlo sampling, another name for Particle Filters [140]. Monte Carlo methods are used when the determination of the probability distribution $p(x_i|z_{1:i})$ is difficult or impossible. One way of dealing with this problem is to use a proposal distribution $q(x, y)$. Random samples are drawn from the latter and each one is weighted according to a function proportional to the target distribution $p(x)$. This samples are called particles and are recursively updated with the incoming measures. Their weights are recomputed at every iteration, updating the resulting distribution.

In our scenario, the location of the museum visitor, roaming around with her/his mobile guide, evolves in time and the only way we have to measure this evolution are the very noisy measures of the mobile device. As we saw in 4.7.1 multi-path effects on the electro-magnetic signal's propagation and non isotropic antenna radiation patterns make it impossible to determine exactly where we could be if only the RSSI values are given. To perform this task we consider our radio-maps, and the relative set of $k-tuples$, as a proposal distribution $q(x, y)$ of possible user locations. This initial state of the algorithm is shown graphically in figure 5.13. The red dots are all the hypothesis that have been

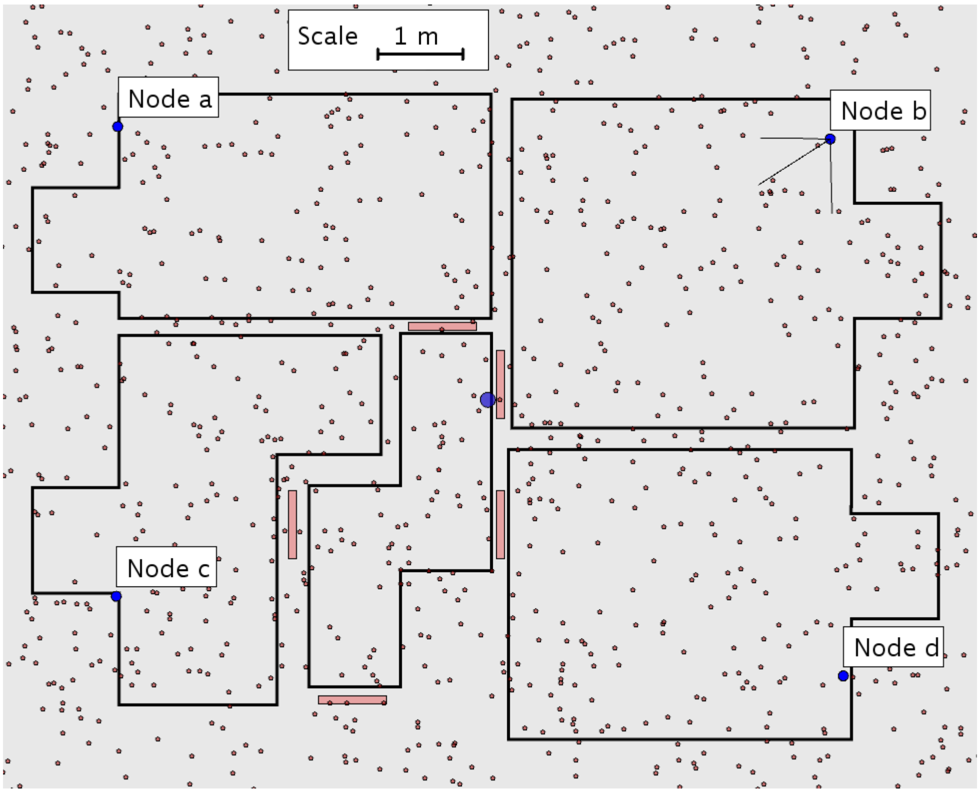


Figure 5.13: Particles drawn randomly that have not been weighted.

drawn from $q(x, y)$. Particles have all the same weight and thus we can not make any decision regarding where the user is. As we start the measuring process, that is we start capturing the advertising packets of the BLE anchors, the radio-maps are generated and the particles are weighted. In figure 5.14 the size of each particle is related to its weight. The bigger ones are good candidates of being real user locations. In the figure we also can see the radio-maps. They have been scaled down for illustration purposes, in reality each of them covers almost the entire area.

Since we are interested in keeping in the current state only a set of good candidate locations we must perform a selection amongst all of our initial hypothesis. For this purpose in our positioning algorithm we adopted the Sequential Importance Resampling (SIR) Particle Filter [41]. In this implementation the particles set itself is updated by performing a re-sampling (particles with lower weights are removed from the set while new ones are generated by using the roulette wheel algorithm). For more details on SIR and Monte Carlo Methods in general, refer to [41].

Authors of [41] suggest to resample when the effective samples size that contributes

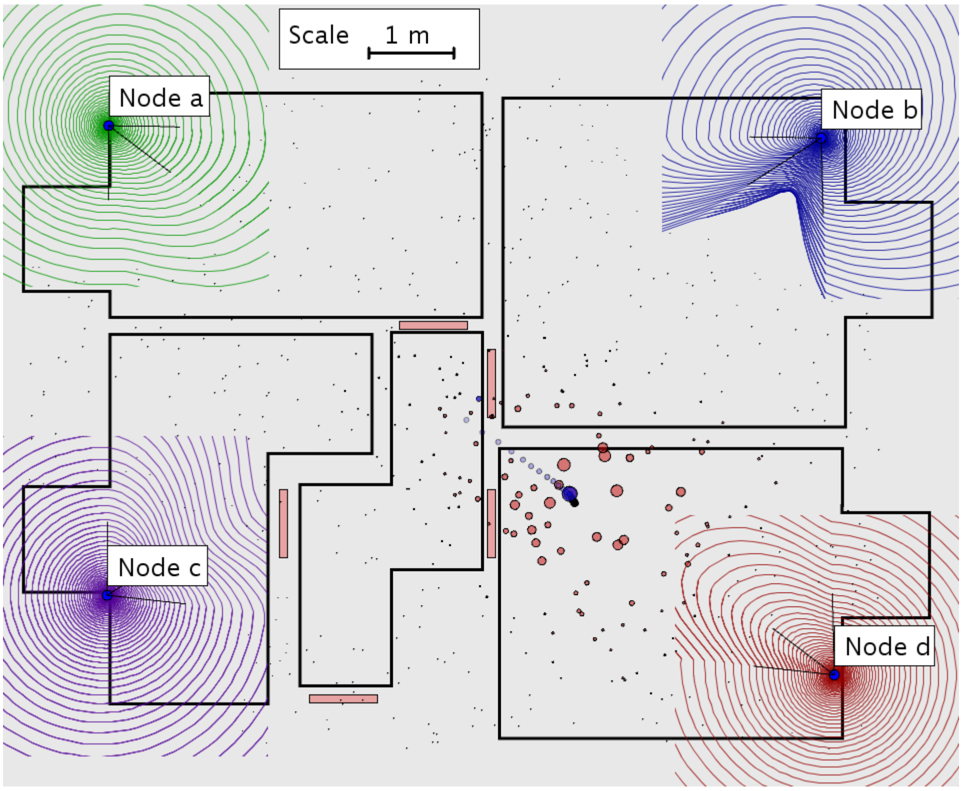


Figure 5.14: Particles after the weighting step.

to the distribution drops below a certain threshold. The effective number of particles that are contributing to the distribution can be computed as :

$$N_{eff} = \frac{1}{\sum_{i=1}^{N} (w_k^i)^2} \tag{5.4}$$

where smaller N_{eff} means a larger variance for the weights, that is more degeneracy in the particle set. In [41] it is suggested to resample every time $N_{eff} < \frac{N}{2}$.

The roulette wheel selection algorithm, a visual example in figure 5.15, is a fitness-proportionate selection technique used to generate a new population of individuals. the individuals that fit better will be redrawn more times than those that have a lesser weight and as a result we will have a set of hypothesis with higher average probability of representing the solution to our positioning problem.

SIR performance depends on how well the proposal distribution fits the posterior one, the one that we are trying to evaluate. Higher accuracy and computational efficiency can be achieved as the similarity between those two distributions increases.

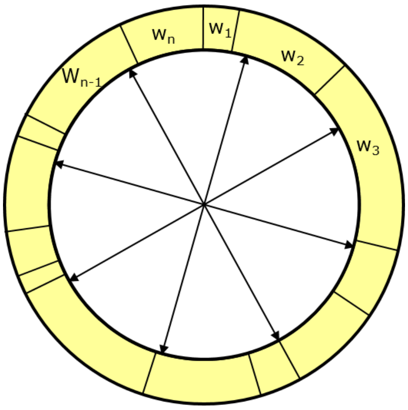


Figure 5.15: Roulette wheel selection. Each particle is represented by a circular sector proportional to its weight. The selection is done randomly on all the circle.

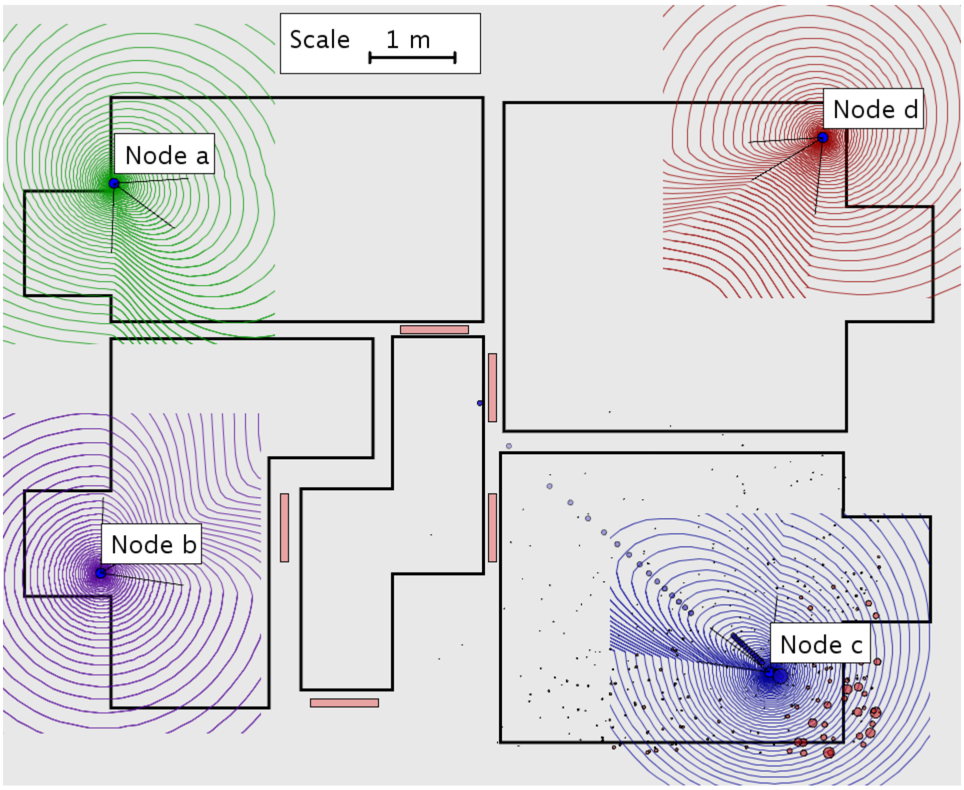


Figure 5.16: Particles "gather" in area that represents the possible location.

After the re-sampling step, particles "gather" around an area that most likely represents the current location. This is shown in figure 5.16. Particles size does not indicate their weight, as it in the previous figures. We can still see particles that have survived the roulette wheel selection even if they are not good candidate solutions. The fittest ones, on the other hand, have produced more offspring. If the re-sampling was done by simply copying a selected particle we would end up, after several iterations, with having only few possible solutions replicated many times. This is referred to as the sample impoverishment problem. To overcome this issue, once a particle has been chosen by the roulette wheel we move it's offspring randomly around the original particle's position by a certain amount. This guarantees that particles do not collapse to just few, because even if that happens and we have 10 particles centered at $(x1, y1)$ by randomly moving each of them we generate new particles that will most likely have different weights in the next iteration. After several iterations, the particles define an area of possible user locations and the current one is represented by the average weighted location of all the particles.

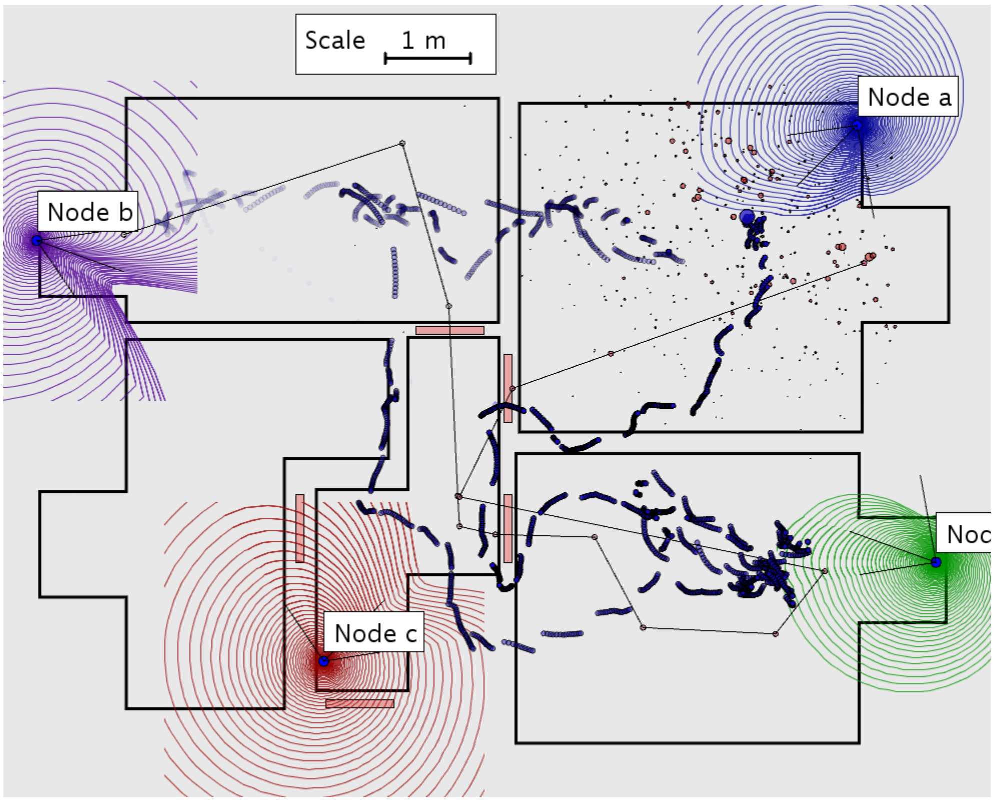


Figure 5.17: Positioning algorithm evolution over time.

While the visitor moves around the mobile device keeps capturing BLE advertisements. This new data feeds the next iteration of the particle filter which results in the particles that best represent the new state being weighted more and generating more offspring in the re-sampling step than particles that were more important in the previous state. In figure

5.17 we show the result of the particle filter iteration over time. The cloud of particles has moved along the green dotted path. The straight line going from **Node c**, on the lower right corner, to **Node b** and after that to **Node d** represents the trajectory followed by the user. The green path looks very similar to the ground truth trajectory but the results are not always so good. As stated before the accuracy of the SIR algorithm is strictly correlated with the grade of similarity that is achieved with the proposal distribution, e.g. the radio-maps in our case. Indeed, the radio-map generation and the weighting function to be employed in algorithm must be studied further.

5.4 Deployment and experimental results

The positioning algorithm is still a work in progress and currently runs in the form of a simulation that takes in input real captures of the Bluetooth Low Energy nodes placed in my house in Torino, Italy. I used 4 beacons placed at the corners of the house. The red squares in the images show where the doors are. This information is not currently being used by the positioning algorithm since one of the requirements was the self healing and adaptation without any knowledge of the environment. With 4 beacons I was able to cover around 60 square meters of space.

Data was collected with a Nexus 5 Android device that runs a custom application. The latter was developed to help gather the data and also for placing the landmarks of the users trajectory. While testing with different devices it was noted they different vendors implement the Bluetooth stack differently. A Nexus 6 device for example does not report all the captured advertisement packets, instead it looks like the device filter the incoming packets from the same device. This could pose a problem since we rely on those advertising packets to update our particle filter.

The algorithm has been implemented in the Processing environment[5] in the Java language. Being implemented in Java means that the algorithm could be easily ported to an Android mobile device.

In figure 5.18 the connected path represents the trajectory followed. The blue dotted path, is the history of the predictions of the positioning algorithm. Table 5.1 shows the results of execution of the positioning algorithm. Since the PF algorithm runs continuously we compute the distance with the path stops for the first estimate after the spot has been

[5]The Processing website https://processing.org/

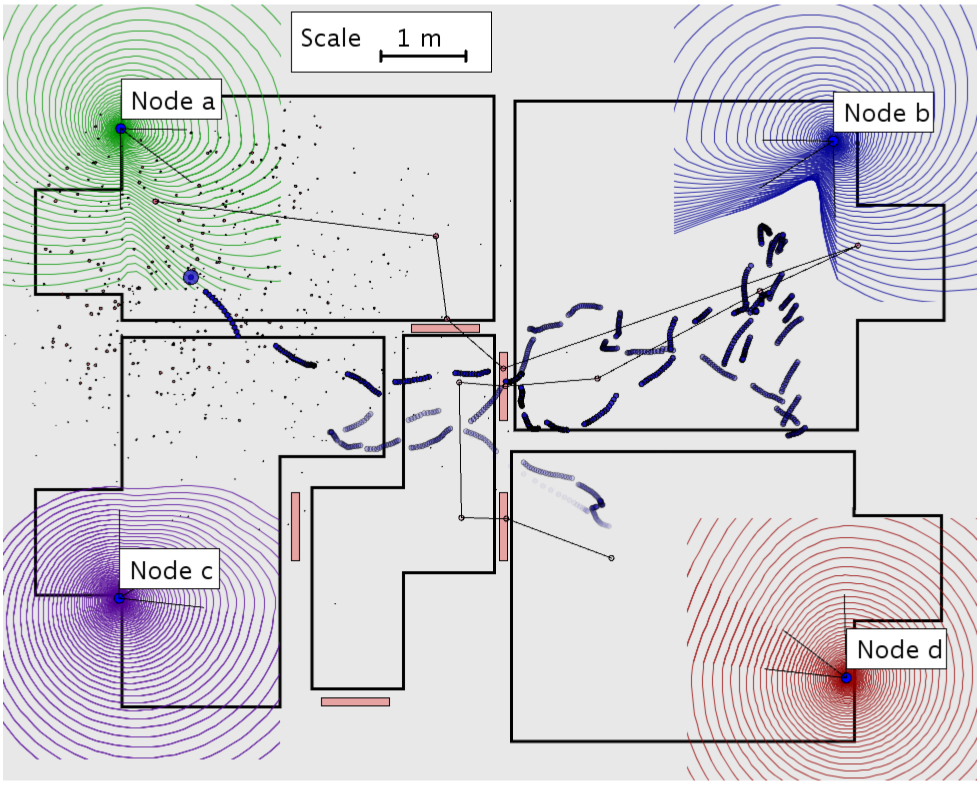


Figure 5.18: Result of the execution of the positioning algorithm. The radio-maps are scaled down for illustration purposes.

reached. The maximum error is under 2m, instead for the path represented in figure 5.19 the maximum error is 2.8m as reported in table 5.2. The performance of the algorithm is also related to the speed at which the visitor is moving. If the movements are too fast the particle filter needs more time to converge towards an acceptable solution. This is related to the measuring frequency, if it was possible to capture advertisements at a frequency of 100 Hz the algorithm will have more measures and will execute more iterations of itself.

Table 5.1: Precision of the PF algorithm with respect to path in figure 5.18.

Control Point	**Location**		**PF Estimate**		**Error**
	x (m)	y (m)	x (m)	y (m)	(m)
1	1.4	1.8	1.3	1.4	0.4
2	0.2	1.4	1.1	1	1
3	-0.3	1.4	-0.8	0.1	1.4
4	-0.4	-0.2	0	0	0.4
5	0.2	-0.2	1.1	-1.1	1.3
6	1.3	-0.3	1.5	-0.6	0.4
7	3.2	-1.3	3.4	-1.5	0.3
8	4.3	-1.8	3.2	-2	1.1
9	0.1	-0.4	1.1	0.2	1.2
10	-0.5	-1	0.4	0.3	1.6
11	0.6	-1.9	-0.2	-0.3	1.8
12	-3.9	-2.4	-3.5	-1.5	1
Mean Error :					1.0

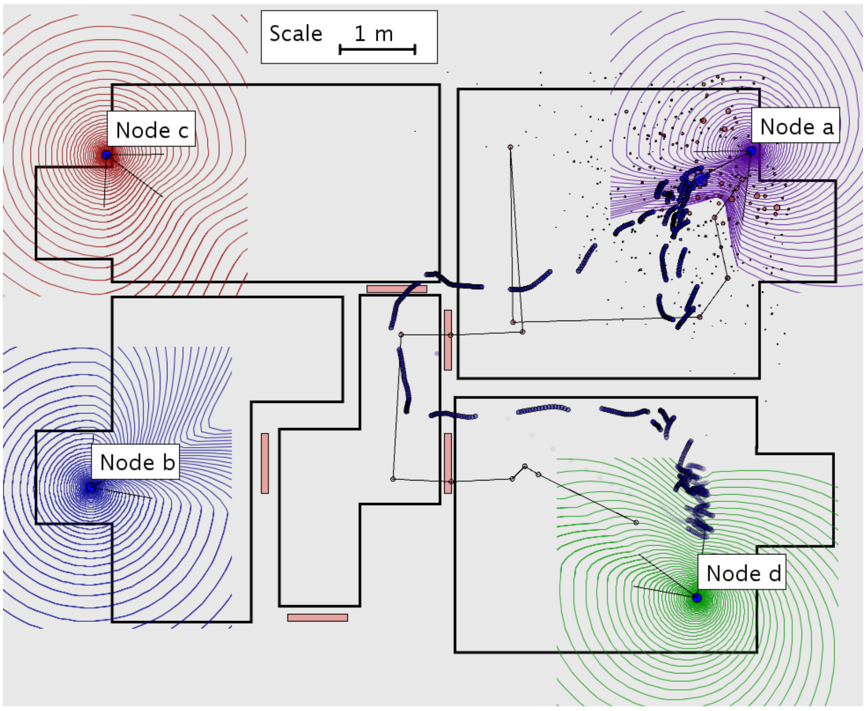


Figure 5.19: Positioning algorithm evolution over time.

Table 5.2: Precision of the PF algorithm with respect to path in figure 5.18.

Control Point	**Location**		**PF Estimate**		**Error**
	x (m)	y (m)	x (m)	y (m)	(m)
1	2.7	2.3	3.4	1.5	1.1
2	1.4	1.6	3.3	1.7	1.9
3	1.2	1.5	3.3	1.7	2.1
4	1	1.7	3.1	1	2.2
5	0.2	1.7	2.8	0.8	2.8
6	-0.6	1.7	0.1	0.8	1.1
7	-0.5	-0.3	-0.5	-0.6	0.3
8	0.2	-0.2	0	-1	0.8
9	1.1	-0.3	1.2	0.9	1.2
10	1	-2.8	2.9	-2.1	2.0
11	1	-0.4	3	-0.6	2.0
12	3.5	-0.5	3.1	-0.5	0.4
13	3.9	-1	3.3	-0.5	0.8
14	3.7	-1.8	3.4	-1.8	0.3
Mean Error :					1.4

Figure 5.19 and table 5.2 present the estimate of the visitor's motions and the results of the PF algorithm for another path. The mean error is 1.4m, a little bit higher than the one for the previous path, but still under the 2m precision range that represented my initial goal.

Turning off the WiFi router

All these trials were run in a "real world" environment. There were always at least 10 other WiFi networks of the surrounding apartments, who thanks to multipath effects might interfere with the electro-magnetic signals emitted from the BLE nodes. Since the strongest network was my own I decided to turn it off, together with the cordless phone and other wireless appliances with the purpose of evaluating if the precision of the algorithm would improve in these conditions. Figure 5.20 depicts the path and the location estimates of the indoor positioning algorithm.

The absence of my own wireless appliances did not improve much the accuracy of the algorithm. In table 5.3 we can see two errors in the range of 6 meters. For those particular locations the visitor moved too fast, but after a few iterations the estimate error fell again

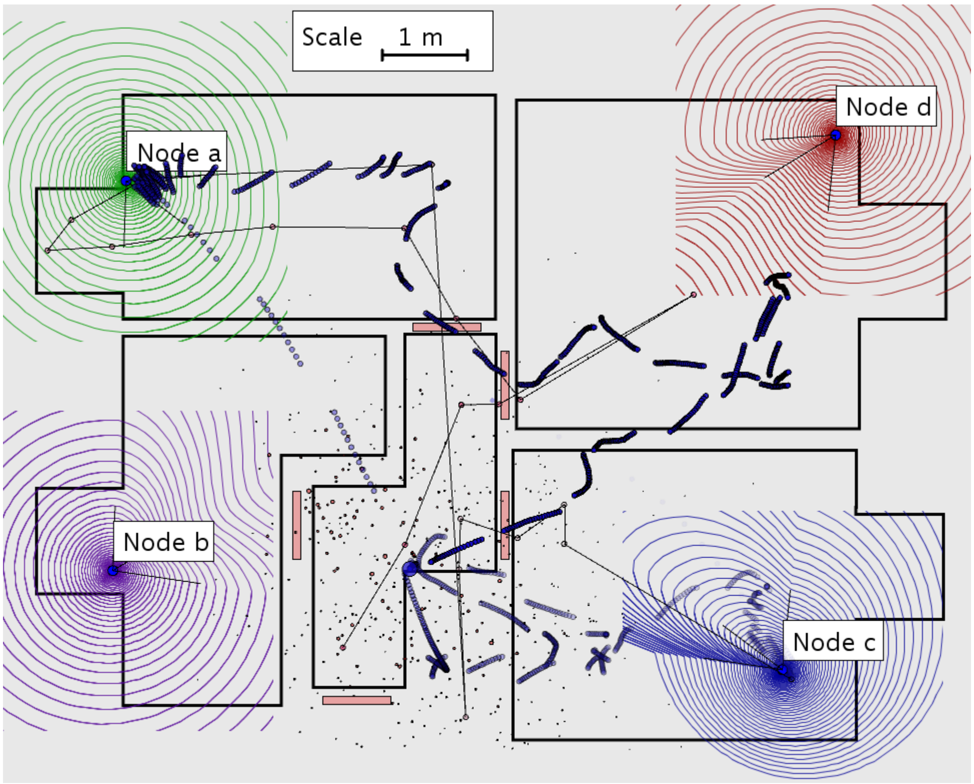


Figure 5.20: Positioning algorithm evolution over time with the WiFi router turned off.

under the 2m threshold.

Table 5.3: Positioning algorithm with WiFi turned off. Reference path in figure 5.20.

Control Point	**Location**		**PF Estimate**		**Error**
	x (m)	y (m)	x (m)	y (m)	(m)
1	3.5	3.3	3.5	3.1	0.2
2	0.8	1.7	2.9	2.1	2.1
3	0.8	1.2	1.6	1.7	0.9
4	0.3	1.6	1.3	2.8	1.6
5	-0.4	1.4	-0.8	1.7	0.5
6	-0.4	2	-0.4	2.3	0.3
7	-0.3	3.7	0.7	3.1	1.2
8	-0.7	-2.8	-0.6	3.1	5.9
9	-4.1	-2.6	-0.6	3	**6.6**
10	-4.9	-2.1	-4	-2.5	1
11	-5.2	-1.8	-4.1	-2.5	1.3
12	-4.5	-1.8	-3.9	-2.6	1
13	-3.5	-1.9	-3.8	-2.6	0.8
14	-2.6	-2	-2.2	-2.6	0.7
15	-1	-2	-0.8	-2.2	0.3
16	-0.4	-1	-0.7	-1	0.3
17	0.3	0	1.3	-0.9	1.3
18	2.4	-1.2	3.5	-0.3	1.4
19	2.4	-1.2	2.9	-0.4	0.9
20	0.1	0	2.9	-0.4	2.8
21	-0.4	0.1	2.3	0.2	2.7
22	-1	1.7	1	1.1	2.1
Mean Error :					1.6

5.5 Conclusions

The indoor positioning system was designed with the goal of providing an unobtrusive positioning/tracking system that could be used both to facilitate the visitors' interaction with the mobile guide and to provide a tool that could enable on-line analysis of the users' behaviors. The positioning system itself is not enough to offer an adaptive museum guide that changes its contents based on the behavior of the visitor. The inertial motion sensors of mobile devices can be used to refine the evolution of the visitors' movements; the compass can be used to determine user's orientation. This data, together with the interactions with the mobile guide (e.g. time spent reading artworks details, accessed artworks etc.) can be interpreted leading to the identification of the current user's profile. A recommender system can then adapt the content of the mobile guide according to this profile.

Differently form other existing approaches to this kind of problem, the system has been designed by taking into consideration the specific needs of the museum ecosystem: having the smallest impact on the building (that can often be an historical monument, subject to many constraints), being easy to deploy and maintain, relying on self-configuration and having a negligible cost. Indeed I was able to cover around 60 squared meters with only 4 BLE beacons that cost 10-25 $ each. For a greater area, let's say 4000 square meters we would need almost 80 nodes to cover the whole area at a maximum hardware cost of 2000 $. Most probably the nodes could be deployed at more than 8 meters distance from each other, resulting in a sparser grid that would reduce the hardware costs of the system.

The overall precision of the designed system (about 2m) is enough to allow the proposed aim and its capability to self adjust to changing radio-environment conditions makes it suitable for dynamic situations where rooms may be at different times fully crowded or almost empty.

At the present moment the indoor positioning algorithm results seem promising but it needs further improvements. One possible direction is to experiment with the generation of the radio-maps of the signal propagation. Perhaps a different path-loss model needs to be used that takes into account also the different walls that the electro-magnetic waves travel through when going from one beacon to the other. To take walls into consideration we need an updated map of the environment. The latter can be downloaded by the mobile guide automatically when available and could also be used to control the movement of the particles of the particle filter by using rules that inhibit a particle to travel through a wall. The production of this map is the main cost of this process and does not represent a significant increase if compared when a new fingerprinting session, needed if we used a positioning system based on this principle every time the environment changes.

The positioning algorithm needs also to be assessed and verified in a larger environment with more than few beacons. In this scenario we could improve the algorithm performance by firstly detecting the macro-area where the user might be (accuracy between 5 and 10 m). For this purpose we could use long range Bluetooth Low Energy anchors. BlueGiga reports operating ranges of up to 400m [6]. Real world usage will most certainly result in lower range, but if these modules do achieve 100-150 meters then we could use them to

[6]BlueGiga BLE121LR, Bluetooth Smart Long Range Module, web page: https://www.bluegiga.com/en-US/products/ble121lr-bluetooth-smart-long/

identify the which cells (each one composed of several beacons) might be more plausible for the visitor's location. Given this subset of areas we could then execute our positioning algorithm only for the BLE beacons present in that region.

Chapter 6

Conclusions

Mobile museum guides can play an important role in cultural heritage experiences mainly by facilitating the meaning-making process. If the variety of services offered can indeed satisfy users' needs, the visitors' experience results to be actually enriched. Modern mobile devices are powerful enough to offer a variety of contents enriched with images, audio tracks, video clips and even non-conventional stimuli (as is the case of mobile games for example). Mobile guides should not be intended as a substitution of the museum experience but as a companion that guides the visitor through the artworks on display and provides the right amount of information in the right time without being distracting nor too difficult to use. There should be no need to learn how to use these systems and this can be achieved through appropriate interaction design choices. The limited size of mobile devices' displays poses another problem to the design process: user interactions and contents have to be properly devised by taking into account the sizes and input/output capabilities of the modern tablets and smartphones. They should not be thought of as static systems whose goal is to offer insights on every detail of the masterpieces on display. Mobile guides should harness the visitor's context in order to "understand" who the visitor is with the purpose of better adapting their contents to this particular visitor. If the system is able to infer its user from her/his actions, movement and interactions with the mobile guide itself, then it is possible to exploit the situated interactions paradigm.

Visitors do not have all the same needs and the designers of the guide must take into account this diversity. One way of dealing with this diversity is to propose a set of predetermined tours, as is the case presented in this thesis, with the mobile guide "Step by Step". This approach has the drawback of determining a limited set of possible ways in which the museum can be explored. Nevertheless, it can be helpful for visitors who do not have a clear plan in mind on how they should organize their visit. Another approach is to let the users roam freely in the environment and then offer contents on request. To be effective this kind of interaction must be supported by an indoor positioning system that detects the visitor's location and orientation. In MusA this was achieved by using an optical indoor positioning system that makes use of custom two-dimensional markers. While being very precise, this system needs the user's intervention, since the user has to point the tablet camera towards the marker. Furthermore, before performing that action, the visitor has to find where the marker is, leading to a more complicated interaction and even a waste of time. The indoor positioning system should not require intervention from the user and it should work silently in background with the double goal of offering content based services and a tool for collecting insights on the visitors' behaviors inside the cultural venue. These data could be used not only by museum curators to assess the effectiveness of the organization of the exhibits, but also to understand and identify eventual patterns of visitor behavior. The corresponding models and the data coming from the indoor positioning system could then be used to feed the content adaptation engine: different visiting styles mean different needs and interests.

Contents should also adapt to the changing levels of user engagement during the museum experience. At the beginning of a tour visitors are usually more open to new stimuli than at the end of the visit: the mobile guide should keep track of this aspect of the user's context and act accordingly by presenting an appropriate amount of information. This means that artworks contents should be designed in a modular way and not just as plain textual guides. Modularity makes it possible to customize the contents, based on user's perceived needs and capabilities by adding or removing information that seem not relevant at that particular moment of the visit. It must be noted that the production of this kind of content is not an easy task: The second version of the "Step by Step" guide required a cultural heritage expert to work for 6 months in order to produce innovative presentations for roughly 200 masterpieces.

The situated interactions experimented within the MusA experience with the mobile guides and the two location based games were appreciated by the visitors and confirmed the effectiveness of mobile guides and games both in terms of user engagement and learning outcomes. Adult visitors appreciated the possibility to access information regarding the artworks in their current location but found the marker finding and pointing process annoying and not immediate.

The two games targeted a different audience than the mobile guide, "Intrigue at the museum" was built with children in mind (7- 13 years old) while "Gossip at the palace" was designed for teenagers. "Intrigue at the museum" made use of gamification techniques to provide children with a pleasant and rewarding experience, combining the exploration of the halls with the provision of activities that could not only foster the acquisition of knowledge about the exhibits but also generate a positive attitude towards the exploration of the venue and museums in general. Post-game interviews showed that in this case marker-hunting was highly appreciated by young visitors who saw it as another interesting activity to carry-on while in the museum. "Gossip at the palace" makes use of a back-story to keep the user engaged while exploring the cultural venue, an example of a storytelling approach used to arise interest and motivation to continue the visit. The adoption of game mechanics entailing the acquisition of points and badges fostered visitors' motivation and will to explore the museum environment, not only to satisfy curiosity but also to enable a sense of personal reward. The two mobile games proved that a museum visit can be more enjoyable and interesting by offering non-conventional stimuli to the young visitors.

The Bluetooth Low Energy based indoor positioning system proposed in chapter 5 was designed with the goal of providing an unobtrusive positioning/tracking system that could be used both to facilitate the visitors' interaction with the mobile guide and to provide a tool that could enable on-line analysis of the users' behaviors. The overall precision of the designed system (about 2m) is enough to reach the proposed aim and its capability to self adjust to changing radio-environment conditions makes it suitable for dynamic situations where rooms may be at different times fully crowded or almost empty.

Differently from other existing approaches to this kind of problem, the system has been designed taking into consideration the specific needs of the museum ecosystem: having the smallest impact on the building (that can often be an historical monument, subject to many constraints), being easy to deploy and maintain, relying on self-configuration and having a negligible cost. The positioning system itself is not enough to offer an adaptive museum guide that changes its contents based on the behavior of the visitor: for instance, the inertial motion sensors of mobile devices can be used to refine the evolution of the visitors' movements; the compass can be used to determine user's orientation. This data, together with the interactions with the mobile guide (e.g. time spent reading artworks details, accessed artworks etc.) can be interpreted leading to the identification of the current user's profile. A recommender system can then adapt the content of the mobile guide according to this profile.

6.1 Future work

This thesis has left several open paths that can be followed to further explore the possibilities offered by situated interactions, especially in informal learning environments such as museums and cultural heritage sites.

To verify the effectiveness of this kind of interactions and assess the outcomes of these experiences in terms of visitors' satisfaction, enjoyment and learning, more work needs to be done on the technological side. Technology is responsible for capturing in an unobtrusive and non distracting way the visitor's context. Once there is enough available information about user's behavior in cultural venues social sciences findings regarding the way in which museum learning process happens and the studies related to motivational factors that push the visitors to learn can be used to properly investigate the detected behaviors and propose new kinds of interactions with the displayed artworks.

As any other technology, the positioning algorithm may be further improved. One possible direction is to experiment with the generation of the radio-maps of the signal propagation: a different path-loss model needs to be used, that takes into account also the different walls that the electro-magnetic waves travel through when going from one beacon to the other. To take walls into consideration we need an updated map of the environment. The latter can be downloaded by the mobile guide automatically when available and could also be used to control the movement of the particles of the particle filter by using rules that inhibit a particle to travel through a wall. The production of this map is the main cost of this process, but does not represent a significant increase if compared with a new fingerprinting session, needed if we used a positioning system based on this principle every time the environment changes.

Once the context harnessing process is assessed, to determine the visitor profile we could employ a machine learning algorithm, trained with previously tracked profiles. The final piece of the puzzle is represented by a recommender system that is the component responsible for deciding what should be presented to the visitor.

Bibliography

[1] Erwin Aitenbichler and Max Mühlhäuser. An ir local positioning system for smart items and devices. In *Distributed Computing Systems Workshops, 2003. Proceedings. 23rd International Conference on*, pages 334–339. IEEE, 2003.

[2] David Alciatore and Rick Miranda. The best least-squares line fit. In *Graphics gems*, pages 91–97. Academic Press: Waltham, MA, USA, 1995.

[3] Marco Altini, Davide Brunelli, Elisabetta Farella, and Luca Benini. Bluetooth indoor localization with multiple neural networks. In *Wireless Pervasive Computing (ISWPC), 2010 5th IEEE International Symposium on*, pages 295–300. IEEE, 2010.

[4] Angeliki Antoniou, George Lepouras, Stavroula Bampatzia, and Hera Almpanoudi. An approach for serious game development for cultural heritage: Case study for an archaeological site and museum. *Journal on Computing and Cultural Heritage (JOCCH)*, 6(4):17, 2013.

[5] Carmelo Ardito, Christos Sintoris, Dimitrios Raptis, Nikoleta Yiannoutsou, Nikolaos Avouris, and Maria Francesca Costabile. Design guidelines for location-based mobile games for learning. In *International Conference on Social Applications for Lifelong Learning*, pages 96–100, 2010.

[6] Mohamed M Atia, Aboelmagd Noureldin, and Michael J Korenberg. Dynamic online-calibrated radio maps for indoor positioning in wireless local area networks. *Mobile Computing, IEEE Transactions on*, 12(9):1774–1787, 2013.

[7] Rosnita Baharuddin, Dalbir Singh, and Rozilawati Razali. Usability dimensions for mobile applications—a review. *Res. J. Appl. Sci. Eng. Technol*, 5:2225–2231, 2013.

[8] Paramvir Bahl and Venkata N Padmanabhan. Radar: An in-building rf-based user location and tracking system. In *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, volume 2, pages 775–784. Ieee, 2000.

[9] Artur Baniukevic, Christian S Jensen, and Hua Lu. Hybrid indoor positioning with wi-fi and bluetooth: Architecture and performance. In *Mobile Data Management (MDM), 2013 IEEE 14th International Conference on*, volume 1, pages 207–216. IEEE, 2013.

[10] Claudia Barberis, Andrea Bottino, Giovanni Malnati, and Paolo Montuschi. Experiencing indoor navigation on mobile devices. *It Professional*, 16(1):50–57, 2014.

[11] Jürg Baus, Keith Cheverst, and Christian Kray. A survey of map-based mobile guides. In *Map-based mobile services*, pages 193–209. Springer, 2005.

[12] F Bellotti, R Berta, A De Gloria, G Panizza, M Pellegrino, and L Primavera. Designing serious games for cultural heritage purposes. *Digital Games and Learning*, pages 252–261, 2011.

[13] Francesco Bellotti, Riccardo Berta, Alessandro De Gloria, Annamaria D'ursi, and Valentina Fiore. A serious game model for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH)*, 5(4):17, 2012.

[14] Francesco Bellotti, Riccardo Berta, Alessandro De Gloria, Edmondo Ferretti, and Massimiliano Margarone. Vegame: exploring art and history in venice. *Computer*, (9):48–55, 2003.

[15] Francesco Bellotti, Riccardo Berta, Alessandro De Gloria, and Victor Zappi. Exploring gaming mechanisms to enhance knowledge acquisition in virtual worlds. In *Proceedings of the 3rd international conference on Digital Interactive Media in Entertainment and Arts*, pages 77–84. ACM, 2008.

[16] Stephen Bitgood. An attention-value model of museum visitors. *Center for Advancement of Informal Science Education: Washington, DC, USA*, 2010.

[17] Philipp Bolliger. Redpin-adaptive, zero-configuration indoor localization through user collaboration. In *Proceedings of the first ACM international workshop on Mobile entity localization and tracking in GPS-less environments*, pages 55–60. ACM, 2008.

[18] L Botturi, A Inversini, and A Di Maria. The city treasure. mobile games for learning cultural heritage. In *Proc. Museums and the Web*, 2009.

[19] A Bruno and GB Pollichino. Sperimentare una nuova metodologia di analisi comportamentale durante le visite nei musei, in "palazzo madama. *Studi e Notizie", 0/1*, pages 209–213, 2011.

[20] Jorge Simarro Cabrera, Henar Muñoz Frutos, Adrian G Stoica, Nikolaos Avouris, Yannis Dimitriadis, Georgios Fiotakis, and Katerina Demeti Liveri. Mystery in the

museum: collaborative learning activities using handheld devices. In *Proceedings of the 7th international conference on Human computer interaction with mobile devices & services*, pages 315–318. ACM, 2005.

[21] Charles Callaway, Oliviero Stock, Elyon Dekoven, Kinneret Noy, Yael Citron, and Yael Dobrin. Mobile drama in an instrumented museum: inducing group conversation via coordinated narratives. *New Review of Hypermedia and Multimedia*, 18(1-2):37–61, 2012.

[22] Li-Wei Chan, Ya-Ying Hsu, Yi-Ping Hung, and Jane Yung-jen Hsu. Orientation-aware handhelds for panorama-based museum guiding system. In *UbiComp 2005 Workshop: Smart Environments and Their Applications to Cultural Heritage*. Citeseer, 2005.

[23] Kuo-En Chang, Chia-Tzu Chang, Huei-Tse Hou, Yao-Ting Sung, Huei-Lin Chao, and Cheng-Ming Lee. Development and behavioral pattern analysis of a mobile guide system with augmented reality for painting appreciation instruction in an art museum. *Computers & Education*, 71:185–197, 2014.

[24] Qian Chen, Haiyuan Wu, and Toshikazu Wada. Camera calibration with two arbitrary coplanar circles. In *Computer Vision-ECCV 2004*, pages 521–532. Springer, 2004.

[25] Xiaopeng Chen, Rui Li, Xuan Wang, Ye Tian, and Qiang Huang. A novel artificial landmark for monocular global visual localization of indoor robots. In *Mechatronics and Automation (ICMA), 2010 International Conference on*, pages 1314–1319. IEEE, 2010.

[26] Yin Chen, Dimitrios Lymberopoulos, Jie Liu, and Bodhi Priyantha. Fm-based indoor localization. In *Proceedings of the 10th international conference on Mobile systems, applications, and services*, pages 169–182. ACM, 2012.

[27] Yisong Chen, Horace Ip, Zhangjin Huang, and Guoping Wang. Full camera calibration from a single view of planar scene. In *Advances in Visual Computing*, pages 815–824. Springer, 2008.

[28] Krishna Chintalapudi, Anand Padmanabha Iyer, and Venkata N Padmanabhan. Indoor localization without the pain. In *Proceedings of the sixteenth annual international conference on Mobile computing and networking*, pages 173–184. ACM, 2010.

[29] Luca Chittaro and Lucio Ieronutti. A visual tool for tracing users' behavior in virtual environments. In *Proceedings of the working conference on Advanced*

visual interfaces, pages 40–47. ACM, 2004.

[30] Jaewoo Chung, Matt Donahoe, Chris Schmandt, Ig-Jae Kim, Pedram Razavai, and Micaela Wiseman. Indoor location sensing using geo-magnetism. In *Proceedings of the 9th international conference on Mobile systems, applications, and services*, pages 141–154. ACM, 2011.

[31] Thomas M Connolly, Elizabeth A Boyle, Ewan MacArthur, Thomas Hainey, and James M Boyle. A systematic literature review of empirical evidence on computer games and serious games. *Computers & Education*, 59(2):661–686, 2012.

[32] Mihaly Csikszentmihalyi. Flow : The psychology of optimal experience. *New York: Harper and Row*, 1990.

[33] Mihaly Csikszentmihalyi. Flow and the psychology of discovery and invention. *New York: Harper Collins*, 1996.

[34] Mihaly Csikszentmihalyi and Kim Hermanson. Intrinsic motivation in museums-what makes visitors want to learn. *Museum news*, 74(3):34, 1995.

[35] Rita Cucchiara and Alberto Del Bimbo. Visions for augmented cultural heritage experience. *MultiMedia, IEEE*, 21(1):74–82, 2014.

[36] Michael Danks, Marc Goodchild, Karina Rodriguez-Echavarria, David B Arnold, and Richard Griffiths. Interactive storytelling and gaming environments for museums: The interactive storytelling exhibition project. In *Technologies for E-Learning and Digital Entertainment*, pages 104–115. Springer, 2007.

[37] David Dean. *Museum exhibition: Theory and practice*. Routledge, 2002.

[38] Sebastian Deterding, Dan Dixon, Rilla Khaled, and Lennart Nacke. From game design elements to gamefulness: Defining "gamification". In *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*, MindTrek '11, pages 9–15, New York, NY, USA, 2011. ACM.

[39] Anind K Dey and Gregory D Abowd. Towards a Better Understanding of Context and Context-Awareness. *Computing Systems*, 40(3):304–307, 1999.

[40] Afke Donker et al. Human factors in educational software for young children. 2005.

[41] Arnaud Doucet and Adam M Johansen. A tutorial on particle filtering and smoothing: Fifteen years later. *Handbook of Nonlinear Filtering*, 12(656-704):3, 2009.

[42] David H Douglas and Thomas K Peucker. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 10(2):112–122, 1973.

[43] Paul Dourish. Seeking a Foundation for Context-Aware Computing Corresponding. *Human–Computer Interaction*, 16:229–241, 2001.

[44] Dana Dudzinska-Przesmitzki and Robin Grenier. Nonformal and informal adult learning in museums: A literature review. *Journal of Museum Education*, 33(1):9–22, 2008.

[45] Christos Emmanouilidis, Remous-Aris Koutsiamanis, and Aimilia Tasidou. Mobile guides: Taxonomy of architectures, context awareness, technologies and applications. *Journal of Network and Computer Applications*, 36(1):103 – 125, 2013.

[46] John Falk and Martin Storksdieck. Using the contextual model of learning to understand visitor learning from a science center exhibition. *Science Education*, 89(5):744–778, 2005.

[47] John H Falk. Contextualizing falk's identity-related visitor motivation model. *Visitor Studies*, 14(2):141–157, 2011.

[48] John H Falk and Lynn D Dierking. *Learning from museums: Visitor experiences and the making of meaning*. Altamira Press, 2000.

[49] Shih-Hau Fang, Chu-Hsuan Wang, Ting-Yu Huang, Chin-Huang Yang, and Yung-Sheng Chen. An enhanced zigbee indoor positioning system with an ensemble approach. *Communications Letters, IEEE*, 16(4):564–567, 2012.

[50] Ramsey Faragher and R Harle. An analysis of the accuracy of bluetooth low energy for indoor positioning applications. In *Proceedings of the 27th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+'14)*, 2014.

[51] Olivier Faugeras. *Three-dimensional computer vision: a geometric viewpoint*. MIT press, 1993.

[52] Martin A Fischler and Robert C Bolles. Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM*, 24(6):381–395, 1981.

[53] Elizabeth FitzGerald. Introduction to location-based mobile learning. In *Education in the wild: contextual and location-based mobile learning in action. A report from the STELLAR Alpine Rendez-Vous workshop series.*, STELLAR Alpine Rendez-Vous workshop, pages 7–9. Learning Sciences Research Institute, University of Nottingham, Nottingham, UK, 2010.

[54] F. Forno, G. Malnati, and G. Portelli. Design and implementation of a Bluetooth ad hoc network for indoor positioning. *IEE Proceedings - Software*, 152(5):223,

2005.

[55] Yasuhiro Fukuju, Masateru Minami, Hiroyuki Morikawa, and Tomonori Aoyama. Dolphin: An autonomous indoor positioning system in ubiquitous computing environment. In *WSTFEUS*, pages 53–56, 2003.

[56] S Gansemer, U Großmann, O Suttorp, and H Dobbelmann. Evaluating a location sensitive multimedia museum guide: Results from a field trial. In *Proceedings of the Digital Cultural Heritage—Essential for Tourism, 2nd EVA 2008 Vienna Conference, Vienna, Austria*, pages 25–28, 2008.

[57] Giuseppe Ghiani, Fabio Paternò, Carmen Santoro, and Lucio Davide Spano. Ubicicero: A location-aware, multi-device museum guide. *Interacting with Computers*, 21(4):288–303, 2009.

[58] Jean-Yves Guillemaut, Alberto S Aguado, and John Illingworth. Using points at infinity for parameter decoupling in camera calibration. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 27(2):265–270, 2005.

[59] Robert Harle. A survey of indoor inertial positioning systems for pedestrians. *Communications Surveys & Tutorials, IEEE*, 15(3):1281–1293, 2013.

[60] Janne Haverinen and Anssi Kemppainen. A global self-localization technique utilizing local anomalies of the ambient magnetic field. In *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, pages 3142–3147. IEEE, 2009.

[61] George E Hein. *Learning in the Museum*. Routledge, 1998.

[62] George E Hein. *Learning in the Museum*. Routledge, 2002.

[63] Jeffrey Hightower and Gaetano Borriello. Location systems for ubiquitous computing. *Computer*, (8):57–66, 2001.

[64] Harlan Hile and Gaetano Borriello. Positioning and orientation in indoor environments using camera phones. *IEEE Computer Graphics and Applications*, 28(4):32–39, 2008.

[65] Sebastian Hilsenbeck, Andreas Moller, Robert Huitl, Georg Schroth, Matthias Kranz, and Eckehard Steinbach. Scale-preserving long-term visual odometry for indoor navigation. In *Indoor Positioning and Indoor Navigation (IPIN), 2012 International Conference on*, pages 1–10. IEEE, 2012.

[66] Ville Honkavirta, Tommi Perälä, Simo Ali-Löytty, and Robert Piché. A comparative survey of wlan location fingerprinting methods. In *Positioning, Navigation and Communication, 2009. WPNC 2009. 6th Workshop on*, pages 243–251. IEEE, 2009.

[67] Eilean Hooper-Greenhill. *Museums and education: Purpose, pedagogy, performance*. Routledge, 2007.

[68] Min-Hsiung Hung, Shih-Sung Lin, Jui-Yu Cheng, and Wu-Lung Chien. A zigbee indoor positioning scheme using signal-index-pair data preprocess method to enhance precision. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pages 548–553. IEEE, 2010.

[69] Yannis Ioannidis, Katerina El Raheb, Eleni Toli, Akrivi Katifori, Maria Boile, and Margaretha Mazura. One object many stories: Introducing ict in museums and collections through digital storytelling. In *Digital Heritage International Congress (DigitalHeritage), 2013*, volume 1, pages 421–424. IEEE, 2013.

[70] Nick Iuppa and Terry Borst. *Story and simulations for serious games: tales from the trenches*. CRC Press, 2012.

[71] Kalle Jegers. Pervasive game flow: understanding player enjoyment in pervasive gaming. *Computers in Entertainment (CIE)*, 5(1):9, 2007.

[72] Hirokazu Kato and Mark Billinghurst. Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In *Augmented Reality, 1999.(IWAR'99) Proceedings. 2nd IEEE and ACM International Workshop on*, pages 85–94. IEEE, 1999.

[73] Michael Kenteris, Damianos Gavalas, and Daphne Economou. Electronic mobile guides: a survey. *Personal and ubiquitous computing*, 15(1):97–111, 2011.

[74] Moritz Köhler, Shwetak N Patel, Jay W Summet, Erich P Stuntebeck, and Gregory D Abowd. Tracksense: infrastructure free precise indoor positioning using projected patterns. In *Pervasive Computing*, pages 334–350. Springer, 2007.

[75] Tobias K Kohoutek, Rainer Mautz, and Andreas Donaubauer. Real-time indoor positioning using range imaging sensors. In *SPIE Photonics Europe*, pages 77240K–77240K. International Society for Optics and Photonics, 2010.

[76] Marguerite L Koole. A model for framing mobile learning. *Mobile learning: Transforming the delivery of education and training*, 1(2):25–47, 2009.

[77] Christian Kray and Jörg Baus. A survey of mobile guides. In *Workshop on HCI in mobile guides, 5th Int. Symposium on HCI with Mobile Devices and Services. Udine, Italy*, 2003.

[78] Tsvi Kuflik, Zvi Boger, and Massimo Zancanaro. Analysis and prediction of museum visitors' behavioral pattern types. In *Ubiquitous Display Environments*, pages 161–176. Springer, 2012.

[79] Tsvi Kuflik, Joel Lanir, Eyal Dim, Alan Wecker, Michele Corra, Massimo Zancanaro, and Oliviero Stock. Indoor positioning in cultural heritage: Challenges and a solution. *2012 IEEE 27th Convention of Electrical and Electronics Engineers in Israel, IEEEI 2012*, pages 1–5, 2012.

[80] Swarun Kumar, Stephanie Gil, Dina Katabi, and Daniela Rus. Accurate indoor localization with zero start-up cost. In *Proceedings of the 20th annual international conference on Mobile computing and networking*, pages 483–494. ACM, 2014.

[81] A Kushki, KN Plataniotis, AN Venetsanopoulos, and CS Regazzoni. Radio map fusion for indoor positioning in wireless local area networks. In *Information Fusion, 2005 8th International Conference on*, volume 2, pages 8–pp. IEEE, 2005.

[82] Teemu Laine, Carolina Islas Sedano, Mike Joy, and Erkki Sutinen. Critical factors for technology integration in game-based pervasive learning spaces. *IEEE Transactions on Learning Technologies*, Vol.3(No.4):294–306, October 2010.

[83] Joel Lanir, Tsvi Kuflik, Eyal Dim, Alan J Wecker, and Oliviero Stock. The influence of a location-aware mobile guide on museum visitors' behavior. *Interacting with Computers*, page iwt002, 2013.

[84] Liqun Li, Pan Hu, Chunyi Peng, Guobin Shen, and Feng Zhao. Epsilon: A visible light based positioning system. In *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*, pages 331–343, 2014.

[85] William Lidwell, Kritina Holden, and Jill Butler. *Universal principles of design, revised and updated: 125 ways to enhance usability, influence perception, increase appeal, make better design decisions, and teach through design*. Rockport Pub, 2010.

[86] Hyuk Lim, Lu-Chuan Kung, Jennifer C Hou, and Haiyun Luo. Zero-configuration, robust indoor localization: Theory and experimentation. 2005.

[87] Hui Liu. Survey of Wireless Indoor Positioning\nTechniques and Systems. 37(6):1067–1080, 2007.

[88] Vincenzo Lombardo and Rossana Damiano. Storytelling on mobile devices for cultural heritage. *New Review of Hypermedia and Multimedia*, 18(1-2):11–35, 2012.

[89] Peter Lonsdale, Chris Baber, Mike Sharples, Will Byrne, Theodoros N Arvanitis, Pat Brundell, and Russell Beale. Context awareness for mobilearn: creating an engaging learning experience in an art museum. *Proc. MLearn 2004: Learning Anytime, Everywhere*, pages 115–118, 2005.

[90] Ioanna Lykourentzou, Xavier Claude, Yannick Naudet, Eric Tobias, Angeliki Antoniou, George Lepouras, and Costas Vassilakis. Improving museum visitors' quality of experience through intelligent recommendations: A visiting style-based approach. In *Intelligent Environments (Workshops)*, pages 507–518, 2013.

[91] Shahzad Malik, Gerhard Roth, and Chris McDonald. Robust corner tracking for real-time augmented reality. 2002.

[92] Shelley Mannion. Beyond cool: Making mobile augmented reality work for museum education. In *Museums and the Web*, pages 11–14, 2012.

[93] Paul Martin, Bo-Jhang Ho, Nicholas Grupen, Samuel Munoz, and Mani Srivastava. An ibeacon primer for indoor localization: demo abstract. In *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings*, pages 190–191. ACM, 2014.

[94] Rainer Mautz. *Indoor positioning technologies*. PhD thesis, Habilitationsschrift ETH Zürich, 2012, 2012.

[95] Stephen J Maybank and Olivier D Faugeras. A theory of self-calibration of a moving camera. *International Journal of Computer Vision*, 8(2):123–151, 1992.

[96] John D McCarthy, M Angela Sasse, and Jens Riegelsberger. Could i have the menu please? an eye tracking study of design conventions. In *People and computers XVII—Designing for society*, pages 401–414. Springer, 2004.

[97] Morris Hargreaves McIntyre. Never mind the width, feel the quality. report for the museums and heritage show. london 2005.

[98] Michela Mortara, Chiara Eva Catalano, Francesco Bellotti, Giusy Fiucci, Minica Houry-Panchetti, and Panagiotis Petridis. Learning cultural heritage by serious games. *Journal of Cultural Heritage*, 15(3):318–325, 2014.

[99] Alessandro Mulloni, Daniel Wagner, Istvan Barakonyi, and Dieter Schmalstieg. Indoor positioning and navigation with camera phones. *Pervasive Computing, IEEE*, 8(2):22–31, 2009.

[100] Frank Nack and Annika Waern. Mobile digital interactive storytelling—a winding path. *New Review of Hypermedia and Multimedia*, 18(1-2):3–9, 2012.

[101] Fiona Fui-Hoon Nah, Yunjie Zhou, Adeline Boey, and Hanji Li. Understanding engagement in educational computer games. *Meaningful Play*, 2012.

[102] Reinhard Oppermann, Marcus Specht, and Igor Jaceniak. Hippie: A nomadic information system. In *Handheld and Ubiquitous Computing*, pages 330–333. Springer, 1999.

[103] Radu Orghidan, Joaquim Salvi, Mihaela Gordan, and Bogdan Orza. Camera calibration using two or three vanishing points. In *Computer Science and Information Systems (FedCSIS), 2012 Federated Conference on*, pages 123–130. IEEE, 2012.

[104] Emin Orhan. Particle filtering. *Center for Neural Science, University of Rochester, Rochester, NY*, 8(11), 2012.

[105] Jan Packer. Learning for fun: The unique contribution of educational leisure experiences. *Curator: The Museum Journal*, 49(3):329–344, 2006.

[106] Jan Packer. Beyond learning: Exploring visitors' perceptions of the value and benefits of museum experiences. *Curator: The Museum Journal*, 51(1):33–54, 2008.

[107] Jan Packer and Roy Ballantyne. Motivational factors and the visitor experience: A comparison of three sites. *Curator: The Museum Journal*, 45(3):183–198, 2002.

[108] Parth H Pathak, Xiaotao Feng, Pengfei Hu, and Prasant Mohapatra. Visible light communication, networking, and sensing: A survey, potential and challenges. *Communications Surveys & Tutorials, IEEE*, 17(4):2047–2077, 2015.

[109] Bryan Patten, Inmaculada Arnedillo Sánchez, and Brendan Tangney. Designing collaborative, constructionist and contextual applications for handheld devices. *Computers & education*, 46(3):294–308, 2006.

[110] Federico Peinado and Pablo Gervás. Transferring game mastering laws to interactive digital storytelling. In *Technologies for Interactive Digital Storytelling and Entertainment*, pages 48–54. Springer, 2004.

[111] Daniela Petrelli. Museums as theatre. In *Proceedings of the Workshop on Affect in Interactions*, pages 107–110. Citeseer, 1999.

[112] Nissanka Bodhi Priyantha. *The cricket indoor location system*. PhD thesis, Massachusetts Institute of Technology, 2005.

[113] Dimitrios Raptis, Nikolaos Tselios, and Nikolaos Avouris. Context-based design of mobile applications for museums: A survey of existing practices. In *Proceedings of the 7th International Conference on Human Computer Interaction with Mobile Devices &Amp; Services*, MobileHCI '05, pages 153–160, New York, NY, USA, 2005. ACM.

[114] Dimitrios Raptis, Nikolaos Tselios, and Nikolaos Avouris. Context-based design of mobile applications for museums: a survey of existing practices. In *Proceedings of the 7th international conference on Human computer interaction with mobile devices & services*, pages 153–160. ACM, 2005.

[115] Léonie J Rennie and David J Johnston. The nature of learning and its implications for research on learning from museums. *Science Education*, 88(S1):S4–S16, 2004.

[116] Branko Ristic, Sanjeev Arulampalam, and Neil Gordon. *Beyond the Kalman filter: Particle filters for tracking applications*, volume 685. Artech house Boston, 2004.

[117] Ivo Roes, Natalia Stash, Yiwen Wang, and Lora Aroyo. A personalized walk through the museum: The chip interactive tour guide. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems*, pages 3317–3322. ACM, 2009.

[118] Irene Rubino, Claudia Barberis, Lara Di Chio, Jetmir Xhembulla, and Giovanni Malnati. Enhancing a museum mobile application through user experience design: A comparative analysis. 2014.

[119] Irene Rubino, Claudia Barberis, Jetmir Xhembulla, and Giovanni Malnati. Integrating a location-based mobile game in the museum visit: Evaluating visitors' behaviour and learning. *Journal on Computing and Cultural Heritage (JOCCH)*, 8(3):15, 2015.

[120] Irene Rubino, Jetmir Xhembulla, Andrea Martina, Andrea Bottino, and Giovanni Malnati. Musa: Using indoor positioning and navigation to enhance cultural experiences in a museum. *Sensors*, 13(12):17445–17471, 2013.

[121] Eileen Scanlon, Ann Jones, and Jenny Waycott. Mobile technologies: prospects for their use in learning in informal science settings. *Journal of Interactive Media in Education*, 2005(2), 2005.

[122] David Schaller. The meaning makes it fun. *Journal of Museum Education*, 36(3):261–268, 2011.

[123] Dieter Schmalstieg and Daniel Wagner. Experiences with handheld augmented reality. In *Mixed and Augmented Reality, 2007. ISMAR 2007. 6th IEEE and ACM International Symposium on*, pages 3–18. IEEE, 2007.

[124] Gerhard Schwabe and Christoph Göth. Mobile learning with a mobile game: design and motivational effects. *Journal of computer assisted learning*, 21(3):204–216, 2005.

[125] Gerald Schweighofer and Axel Pinz. Robust pose estimation from a planar target. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 28(12):2024–2030, 2006.

[126] Fernando Seco, A Jimenez, Carlos Prieto, Javier Roa, and Katerina Koutsou. A survey of mathematical methods for indoor localization. In *Intelligent Signal Processing, 2009. WISP 2009. IEEE International Symposium on*, pages 9–14. IEEE,

2009.

[127] Giuseppe Serra, Marco Camurri, Lorenzo Baraldi, Michela Benedetti, and Rita Cucchiara. Hand segmentation for gesture recognition in ego-vision. In *Proceedings of the 3rd ACM international workshop on Interactive multimedia on mobile & portable devices*, pages 31–36. ACM, 2013.

[128] Beverly Serrell. Paying attention: The duration and allocation of visitors' time in museum exhibitions. *Curator: The museum journal*, 40(2):108–125, 1997.

[129] John S Seybold. *Introduction to RF propagation*. John Wiley & Sons, 2005.

[130] Mike Sharples, Elizabeth FitzGerald, Paul Mulholland, and Robert Jones. *Weaving location and narrative for mobile guides*. Routledge, New York, NY, 2013.

[131] Flavia Sparacino. The museum wearable: Real-time sensor-driven understanding of visitors' interests for personalized visually-augmented museum experiences. 2002.

[132] Maurizio A. Spirito and Alberto Guidarelli Mattioli. On the hyperbolic positioning of gsm mobile stations. In *Signals, Systems, and Electronics, 1998. ISSSE 98. 1998 URSI International Symposium on*, pages 173–177. IEEE, 1998.

[133] Oliviero Stock and Massimo Zancanaro. *PEACH-Intelligent interfaces for museum visits*. Springer Science & Business Media, 2007.

[134] Peter F Sturm and Stephen J Maybank. On plane-based camera calibration: A general algorithm, singularities, applications. In *Computer Vision and Pattern Recognition, 1999. IEEE Computer Society Conference on.*, volume 1. IEEE, 1999.

[135] Lucy Suchman. *Plans and Situated Actions*. 1987.

[136] Tynan Sylvester. *Designing Games: A Guide to Engineering Experiences*. " O'Reilly Media, Inc.", 2013.

[137] Cherry Thian. Augmented reality—what reality can we learn from it. In *Museums and the Web*, 2012.

[138] Roger Y Tsai. A versatile camera calibration technique for high-accuracy 3d machine vision metrology using off-the-shelf tv cameras and lenses. *Robotics and Automation, IEEE Journal of*, 3(4):323–344, 1987.

[139] Ilari Vallivaara, Janne Haverinen, Anssi Kemppainen, and Juha Röning. Magnetic field-based slam method for solving the localization problem in mobile robot floor-cleaning task. In *Advanced Robotics (ICAR), 2011 15th International Conference on*, pages 198–203. IEEE, 2011.

[140] Rudolph Van Der Merwe, Arnaud Doucet, Nando De Freitas, and Eric Wan. The unscented particle filter. In *NIPS*, volume 2000, pages 584–590, 2000.

[141] D Van Opdenbosch, Georg Schroth, Robert Huitl, Sebastian Hilsenbeck, A Garcea, and Eckehard Steinbach. Camera-based indoor positioning using scalable streaming of compressed binary image signatures. In *Image Processing (ICIP), 2014 IEEE International Conference on*, pages 2804–2808. IEEE, 2014.

[142] Giasemi Vavoula and Mike Sharples. Meeting the challenges in evaluating mobile learning: a 3-level evaluation framework. *International Journal of Mobile and Blended Learning*, 1:54–75, 2009.

[143] E. Veron and M. Levasseur. *Ethnographie de l'exposition*. Bibliotheque Publique d'Information, Centre Georges Pompidou, Paris, 1983.

[144] Ling-Ling Wang and Wen-Hsiang Tsai. Camera calibration by vanishing lines for 3-d computer vision. *IEEE Transactions on Pattern Analysis & Machine Intelligence*, (4):370–376, 1991.

[145] Roy Want, Andy Hopper, Veronica Falcao, and Jonathan Gibbons. The active badge location system. *ACM Transactions on Information Systems (TOIS)*, 10(1):91–102, 1992.

[146] Andy Ward, Alan Jones, and Andy Hopper. A new location technique for the active office. *Personal Communications, IEEE*, 4(5):42–47, 1997.

[147] Jenny Waycott, Ann Jones, and Eileen Scanlon. Pdas as lifelong learning tools: an activity theory based analysis. *Learning, Media and Technology*, 30(2):107–130, 2005.

[148] Susan Weinschenk. *100 things every designer needs to know about people*. Pearson Education, 2011.

[149] Mark Weiser. The computer for the 21st century. *Scientific american*, 265(3):94–104, 1991.

[150] Heiko Will, Thomas Hillebrandt, and Marcel Kyas. The fu berlin parallel lateration-algorithm simulation and visualization engine. In *Positioning Navigation and Communication (WPNC), 2012 9th Workshop on*, pages 131–136. IEEE, 2012.

[151] Jane Willis. *A framework for task-based learning*. Pearson PTR, 1996.

[152] Annika Wolff, Paul Mulholland, and Trevor Collins. Storyspace: a story-driven approach for creating museum narratives. In *Proceedings of the 23rd ACM conference on Hypertext and social media*, pages 89–98. ACM, 2012.

[153] Jetmir Xhembulla, Irene Rubino, Claudia Barberis, and Giovanni Malnati. Intrigue at the museum: Facilitating engagement and learning through a location-based mobile game. In *Proceedings of 10th International Conference on Mobile Learning*,

pages 41–48. ERIC, 2014.

[154] Jie Xiong and Kyle Jamieson. Arraytrack: a fine-grained indoor location system. In *Presented as part of the 10th USENIX Symposium on Networked Systems Design and Implementation (NSDI 13)*, pages 71–84, 2013.

[155] Chang-Fa Yang, Boau-Cheng Wu, and Chuen-Jyi Ko. A ray-tracing method for modeling indoor wave propagation and penetration. *Antennas and Propagation, IEEE Transactions on*, 46(6):907–919, 1998.

[156] Yuji Yoshimura, Stanislav Sobolevsky, Carlo Ratti, Fabien Girardin, Juan Pablo Carrascal, Josep Blat, and Roberta Sinatra. An analysis of visitors' behavior in the louvre museum: a study using bluetooth data. *Environment and Planning B: Planning and Design*, 41(6):1113–1131, 2014.

[157] Moustafa Youssef and Ashok Agrawala. The horus wlan location determination system. In *Proceedings of the 3rd international conference on Mobile systems, applications, and services*, pages 205–218. ACM, 2005.

[158] Zhengyou Zhang. A flexible new technique for camera calibration. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 22(11):1330–1334, 2000.

[159] Zhengyou Zhang. Camera calibration with one-dimensional objects. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 26(7):892–899, 2004.

[160] Xiaojie Zhao, Zhuoling Xiao, Andrew Markham, Niki Trigoni, and Yong Ren. Does btle measure up against wifi? a comparison of indoor location performance. In *European Wireless 2014; 20th European Wireless Conference; Proceedings of*, pages 1–6. VDE, 2014.

[161] Yuxin Zhao, Feng Yin, F. Gunnarsson, M. Amirijoo, E. Ozkan, and F. Gustafsson. Particle filtering for positioning based on proximity reports. pages 1046–1052, 2015.

[162] Eric Zimmerman. Narrative, interactivity, play, and games: Four naughty concepts in need of discipline, 2004.