Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Curriculum in Ingegneria Informatica, Gestionale e dell'Automazione

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Senseable spaces: from a theoretical perspective to the application in augmented environments

Ph.D. Dissertation of:
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XV edition - new series

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If we knew what it was we were doing,
it would not be called research, would it?

Acknowledgments

One thousand days are gone, or little more, from that day when I decided to undertake this way. Research means sacrifices, of course, but it was my only opportunity to feed my inborn need of curiosity. It was a change of habits, of friendships, of life. I'll never be regretted of that choice of changing. I sow a ten of countries, uncovered different cultures, learned from the greatest researcher. For this, I'm glad to my supervisor, prof. Emanuele Frontoni. I want to thank him because he trusted in me. Come on, just a fullish could bet on an architect to get a Ph.D. in informatics. I thank Emanuele for being a leader, not a boss like I call him; for being straightforward when it was time to be; for being a friend, when among hundreds, he knew that his suggestion was worth. If I know my passion, now, I owe it to him.

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him of being happy every Tuesday, but I forgot that promise, I just hope to have time to put remedy on it. But having the possibility, I would do it again, without regret. Because being far and busy means slavery for someone, but knowledge is freedom for someone else. Freedom is the most amazing cage that we have. The end of this Ph.D. course, is just a new beginning for us.

Ancona, November 2016

Roberto Pierdicca

Abstract

Given the tremendous growth of ubiquitous services in our daily lives, during the last few decades we have witnessed a definitive change in the way users' experience their surroundings. At the current state of art, devices are able to sense the environment and users' location, enabling them to experience improved digital services. Along with the growing ubiquity of mobile technologies, they can be permitted to interact with the space and, which generally increases the information content of the space, creating synergistic loop between the use of the technology, and the use of the space itself.

Starting from such a premise, this thesis addresses the topic of exploring the relationship between the space, the users' and technologies, investigating how pervasive digital tools can augment our environments and can leverage out new interactivity. Modern technological applications can dynamically deliver different kinds of data to the users, but they also allow for the extraction of data from them. We coined the term *Senseable Space*, to define the kinds of spaces able to provide users with contextual services, to measure and analyse their dynamics and to react accordingly, in a seamless exchange of information.

The research was performed embracing different application domains, with the main goal of understanding the dynamics of a space starting from the knowledge potentially available from users. This is for two reasons: first of all, even if the main activities have been conducted in the Cultural Heritage domain, it is not sufficient to understand the limits and benefits of this paradigm through simple exploration of a single topic. Secondly, different domains have different needs, so that in order to understand the potential of *Senseable Spaces*, it has been fundamental value to compare with different scenario to outline the points of contact among these. Following the paradigm of *Senseable Spaces* as the main thread, we selected a set of experiences carried out in different fields; central to this investigation there is of course the user, placed in the dual roles of end-user and manager. Besides, both indoor and outdoor scenarios have been explored, since the knowledge of the operational condition of a space is a mandatory requirement for application of a particular use of the intended technology.

The main contribution of this thesis lies in the definition of this new paradigm,

realized in the following domains: Cultural Heritage, Public Open Spaces, Geosciences and Retail.

For the Cultural Heritage panorama, different pilot projects have been constructed from creating museum based installations to developing mobile applications for archaeological settings. Dealing with urban areas, app-based services are designed to facilitate the route finding in a urban park and to provide contextual information in a city festival. We also outlined a novel application to facilitate the on-site inspection by risk managers thanks to the use of Augmented Reality services. Finally, a robust indoor localization system has been developed, designed to ease customer profiling in the retail sector. Building up such scenarios and architectures, we have attempted to address the following statement of the problem: are we able to design a space, regardless the domain, capable of bidirectional exchange of data between the space and the user? The thesis also demonstrates how Space Sensing and Geomatics are complementary to one another, given the assumption that the branches of Geomatics cover all the different scales of data collection, whilst Space Sensing gives one the possibility to provide the services at the correct location, at the correct time.

Acronyms

AI Artificial Intelligence

AR Augmented Reality

AH Architectural Heritage

AmI Ambient Intelligence

AOI Area of Interest

API Application Programming Interface

AVM Automatic Vehicle Monitoring

BLE Bluetooth Low Energy

BS Buffer Strips

CAD Computer Aided Design

CH Cultural Heritage

DCH Digital Cultural Heritage

GIS Geographical Information System

GNSS Global Navigation Satellite System

GPS Global Positioning System

HHD Hand Held Devices

HMD Head-Mounted Devices

ICT Information and Communication Technologies

LBS Location Based Services

LCLU Land Cover / Land Use

LOD Level of Detail

MAR Mobile Augmented Reality

MISP Multiple Images Spherical Photogrammetry

MVS Multi-View Stereo

POS Public Open Spaces

POI Point of Interest

SDK Software Development Kit

TTFF Time of First Fixation

TLS Terrestrial Laser Scanner

RSSI Received Signal Strength Indication

SfM Structure from Motion

VR Virtual Reality

UGD Users Generated Data

UUID Universally Unique Identifier

WSN Wireless Sensors Network

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Chapter 1

Introduction. A theoretical perspective from augmented spaces to senseable spaces

"Do we end up with a new experience in which the spatial and information layers are equally important?" With this question, Lev Manovic was introducing, in 2006, the revolutionary concept of *augmented spaces*; in [1], the author synthesizes the space that we leave, made up of two layers: the physical (or tangible) dimension, and the digital (or intangible) one. The dissertation provides a very simple and clear definition of this paradigm: "augmented space is the physical space overlaid with dynamically changing information. This information is likely to be in multimedia form and it is often localized for each user". Now, ten years later, we can witness to the realization of this concept in our daily life. The two dimensions seem to mesh-up, in a seamless relation between real and virtual. This is mostly because latest improvements on mobile devices capabilities are changing the way people interact with their surroundings. Nowadays, devices are able to sense the environment and users' location, enabling them to experience improved digital services. But this is not the only reason. In fact, mobile devices alone can just provide the users with tools (e.g applications) and services that can facilitate them in performing single tasks. Instead, along with the growing ubiquity of mobile technologies, they can be enabled to interact with the space, or better, with the objects that fit that space. And more, other data are produced from this interaction, creating a sort of loop between the use of the technology, and the use of the space itself. Starting from this assumption, this thesis addresses the topic of understanding the relation between the space, people and technologies and investigates how the ubiquity of digital tools can augment our environments and can leverage new ways of interaction. It uncovers how data from sensors can be presented to the observer in an intuitive manner, in the context of the observed environment. In a focal role of this dissertation there is, of course, the user. In the first meaning of augmented spaces in fact, the stereotype imagery was a space with digital ornament, lights, digital signage, with the idea of changing the space just with dynamic multimedia information projected on the walls. Let us say that in this kind of space, the human presence is just a passive spectator of a scene. Modern technological applications can dynamically deliver different kind of data to the users, or extract data from them, transforming the space from augmented to *Senseable*. In other words, the delivery of information to users in space, and the extraction of information about those users, are closely connected and pave the way towards the"*ability to sense and make sense*" of it. The research was experienced covering a wide spectrum of domains and topics, addressing the problem of defining new methods of observing the dynamics of a space, collecting data and using them with the twofold purpose of providing services, and enhancing the space itself.

The introduction Chapter of the present work is aimed at providing a wide overview about the concept of *Senseable Space*, starting from the growing connection between the space and the technology; afterwards, we make a focus over the most famous laboratory, taken as a reference for this work, which deal with these new concepts of Space Sensing: the Senseable City lab that Carlo Ratti founded in 2003 at the MIT in Boston, USA. As the author of this thesis, Carlo Ratti is an architect which fulfilled the cause of interweaving his background of planner and designer with the usage of digital methods to uncover spaces' dynamics, analysing them in real time and predicting their changes. The perspective of this work is provided highlighting the importance of data, regardless the type of data we are dealing with. We generally use to think that every discipline has its own kind of data, like compartments that cannot mesh up and support each other. But so often we forget that because of its nature, a data represent a measure. If we deal with spatio-temporal data, or geo-spatial data, we are measuring an event. In this, geomatics plays a pivotal role in terms of data acquisition from different data sources. For long time, geomatics has been considered the discipline to take measurement, rather then to measure an event. The provisioning of affordable data, their management, their loss less simplification is essential to provide users with services that improve their experience of a *Senseable Space*.

The multidisciplinary nature of the presented work arose from the above mentioned assumptions.

With the second Chapter we provide a review the state of art about technologies and application that, more then others, have demonstrated of being suitable for the development of new kinds of interaction and to make a space *Senseable*, with low costs. Among the others, Augmented Reality (AR) is the cutting edge technology in which we decided to investigate, since it embraces both the concepts of sensing the space and giving information. A particular focus have been devoted to the Cultural Heritage (CH) domain, one of the main research interest of the author, giving a wide overview about the research works conducted in the last decade around this domain. We will show how the use of AR incredibly contributed to the promotion of CH.

The use cases faced during the research activity are collected in Chapter 3. It represents the summa of different experiences, activities and best practices which can help to contribute, compared with the state of art, to better understand the paradigm of a *Senseable Space* in different research areas. Each use case have been divided, to facilitate the reader, into a hierarchical scheme: *Scenario*, *System Architecture*, *Results*. In this way we thought to better highlight the benefits that the different approaches (in different domains), brought to the users. Chapter 4, besides arguing over the possibilities that the proposed paradigm opens up in different topics, summarizes also the challenges, the open issues and the limitations that require further investigations. From this, we outlined the future works, that are described in the Chapter 5, together with our concluding remarks.

1.1 The relation between spaces, users and technologies

While this new research paradigm of *Senseable Spaces* have been outlined, what is still missing is a description of the "components" that could make it possible. Manovic gave several examples of applications and technologies widely adopted to dynamically deliver data to, or extract data from, physical space. Video surveillance for instance have become ubiquitous. Cameras, are able to serve several purposes: real time tracking, recognition, localization. As well, even if in a completely different way, mobile phones act exactly in the same direction. Using the logs of a devices, we can understand the devices' position (via wireless connections in indoor, via GPS in outdoor) and from it give contextual information. It also makes sense to conceptually connect the surveillance/-monitoring of physical space and its dwellers, and the augmentation of this space with additional data, because technologically these two applications are in a symbiotic relationship. For instance, if one knows the location of a person equipped with a mobile phone, he can send his particular information relevant to that specific location via his mobile phones. Many others are the domain that converge to this problem. Ubiquitous Computing, Augmented Reality, Tangible Interfaces, Wearable Devices, Wireless Sensor Networks (WSN), Ambient Intelligence (AmI), Internet of Things just to quote some. But while the technologies imagined by these research paradigms accomplish their intentions in a number of different ways, the end result is the same: "overlaying dynamic data over the physical space". An old timeless quote by Mark Weiser [2] affirms that the most profound technologies are those that disappear. Despite it was coined more than a decade ago, this sentence is still an important guideline for the development of smart objects. In the early nineties the idea of an environment with pervasive (but not intrusive) computing laid the foundations for Ubiquitous Computing. No revolution in artificial intelligence is needed, just the proper embedding of computers into the everyday world. All the above culminated in the so called (*AmI*), that has definitively changed the way in which visitors interact with the space. We can define AmI a quite new archetype of information technology, designed to allow spaces of any kind to become sensitive, adaptive, and responsive to the needs of the people who live. One of its sub-domain is the Artificial Intelligence (*AI*), which contribution was to support people in their lives, becoming essential for almost every ambit. One of the main objectives of *AI* is to pervade our daily life environments with non-invasive (and conceived) technologies able to supply humans with supplementary knowledge for making better decisions [3]. Towards this direction, research aims to include more intelligence into surroundings, transforming them into digital ambient aware and *Senseable* of human presence. A large number of embedded systems becomes the bridge between humans and computing. Computer-based artefacts are programmed in order to interact, analyse and cooperate with humans (*human computation*). In this field, future research will be carried on to use as much as possible of the human minds in every kind of environment. It is very important to gain users' opinions, asking them to give a feedback. All this data can be coupled together to understand users' needs

Given the above, it is particularly important to underline the crucial role of smart objects for the spreading of *AmI*. In addition to their increasing miniaturization, sensors, actuators, and processing units, they can be purchased at very inexpensive prices.

In the recent years, we witnessed to an improvement in the use of handy smart devices (e.g. mobile phones), insomuch that they are naturally extended to all areas of science like education, health, cultural heritage, entertainment, sports, transportation and many more, into a collaborative way of interaction. However, Pervasive Computing and Artificial Intelligence cannot embrace *AmI* themselves. Indeed, only *AmI* can brings together all these resources as well as many other areas to provide flexible and intelligent services to users acting in their environments [4, 5].

AmI involves several areas: Ambient Assisted Living (*AAL*), video surveillance, group interactions analysis, health care, collaborative context recognition for mobile devices and many others [6, 7, 8]. Generally, vision and image processing are largely used to solve common aspects for the aforementioned fields. The key aspect for *AmI* lays in the possibility to provide services not for user request, but based over the intelligence of the system; this will allow the automatic provision of services depending of the profile and the position of the user experiencing a task. Consequently, the interaction between spaces and users should be done through natural interfaces adapting to them habits and behaviours. To allow this interaction, it is enough to pair with their mobile devices. A network of sensor allows processing the context through the user interaction in real time [9], [10]. Anyway, the development and standardization of new low power consumption and short range wireless technologies have enabled the WSN concept. They present many advantages such as flexibility, adaptability and they are more rigid and consume less power [11]. Today, there are several options for the development of WSN and a wide range of scenarios between standards and technologies can be found [12].

Technology provides analytics taken from users' interaction with spaces; in the retail sector for instance, it can give many information about customers, allowing the retailer to customize the shop to their needs and adapting product arrangements, expositions, design according to their behaviours. Data extracted in this way are objective; indeed, this kind of decision-making process is lead to an objective and reliable data collection. Intellectual approaches are not able to explain the complexity of consumer behaviours, because they arise from many aspects such as cultural context, habits and so on. Several aspects of these problems are currently solved using artificial intelligence and, in particular, vision [13]. Though retail is a suitable example, it is not the only domain exploiting this scenario. In the next paragraph some researches that embody the above are shown.

1.2 The case of Sense*able* city Lab as a reference

Summarizing all the abovementioned topics, researches and technologies into one laboratory, in 2003 Carlo Ratti founded the Sense*able* city lab at the MIT of Boston, USA. The core activities of the lab are oriented towards a pervasive data collection from users, from different data sources, to uncover humans dynamics and to support planners. In fact, since the spaces are generally designed for humans activities, the planning community should be interested from this gathering of information. As stated by Carlo Ratti "the way we describe and understand cities is being radically transformed, alongside the tools we use to design them and impact on their physical structure". Human activities, nowadays, are strictly related to the use of their mobile phones. From them it is possible for instance, in different way that we will describe in the following, to extract data about vehicles. By tracking the single identifier (ID) of each device, or just analysing the phone calls by cells, we can monitor vehicle origins and destinations that is fundamental for the planning process of the infrastructures of a city. Several critical issues, like for instance patterns of congestion, can be derived. Moreover, to understand the benefits from a new area, will be useful to get the pedestrian flows [14] for inferring patterns from humans tracking (e.g. via GPS positioning services).

One of the major works by the lab, is described in [15]. It was conducted in Rome to outline the basis of urban planning using mobile phones and Location Based Services (LBS); exploiting utilities embedded in users' personal devices, a set of applications can be built that exploit the knowledge of the geographical position of a mobile device in order to provide services based on that information. The main assumption from this work was that, if deployed to retrieve aggregated data in cities, LBS could become a powerful tool for urban analysis. But the benefits are not just for the urban planning itself, but also for the whole community living the urban environment. The beneficiaries can be different: single users, (it is now a well established technology the one that allow providing weather forecasts in case of a possible emergency like a flood), group of users (it is recent the success of Pokemon Go application, a game that exploits users' location and AR to discover virtual objects in the real scene, in a sort of collaborative game) and providers (just think to the improvement that can be given to the network's performances whether the provider could know in real time traffic overflows).

The aim of the project "Mobile Landscapes" was to review and introduce the potential of this technology to the urban planning community. In addition, it presents an application in the metropolitan area of Milan, in Italy, based on the geographical mapping of mobile phones usage at different times of the day. In a predefined temporal range, information from mobile phones activities were acquired and analysed with the specific task of urban dynamics understanding. Results seemed to open a new promising line of urban research. Making sense of the unlimited flow of data from the mobile phones infrastructure in the urban context is still unexplored territory. Through the analysis of data coming from base stations, urban planners can gain the ability to monitor rapidly changing urban dynamics, which are difficult to capture by traditional surveys. With the massive spread of hand held devices in the past years, the mobile phones infrastructure could provide an unlimited source of information about the city in ever finer detail. The challenge for urban researchers is to learn how to exploit this information to gain a better understanding of the city.

It is also the case of the study conducted by the Lab to investigate mobile phones traffic records in different cities [16]. From the analysis emerge that it is possible to outline and predict future trends in the way the expansion of the city is going, and it is also possible to infer statistical patterns which have great potential in terms of economics growth. Monitoring and tracking the so-called User Generated Data (UGDs) represent the future pathway for observing, recording, and analysing the dynamics of our environments (i.e. cities, Urban Open Spaces, rural areas, etc.) and, more in general, the behaviour of people who live these spaces. This is the era of Digital Footprints, left by individuals in their daily activities, which can be used as data to make statistics and to extract metrics about our spaces, directly from the users [17]. These information sources are geo-located and embody numerous opportunities, as they offer the possibility of working with high spatial and temporal data, always available and always updated. The advantage of collecting Digital Footprints ranges among different domains, for example security, cities management, retail and cultural heritage. Also in tourism, collecting and analysing Digital Footprints can be useful from the perspective of understanding the tourists' point of view and behaviour in relation to a destination. The tourism experience is nowadays strictly related to the digital approach. In fact, people visiting a new place start their planning from the web, which offers the broader set of opportunity and makes the users' feedback the major criteria of decision. The stage of preparation of the trip is generally followed by the visiting experience, when tourists collect pictures and share insights. Furthermore, it concludes at home, when photographs and experiences are made available to networks of friends or other potential tourists. The tracking, collection and analysis of these Digital Footprints can be a valuable source of information for both tourists and stakeholders. Tourists can take their decisions with more awareness about the place they are going to visit. Digitally active stakeholders, in particular tourism and hospitality operators can easily obtain the users' feedback to evaluate the performances of their offers, and also reach a worldwide public. Tourism data are important for destinations, especially for planning, forecasting tourism demand, marketing, measuring economic impacts and benchmarking. Digital Footprints can be classified as passive and active. Passive tracks are left through interaction with an infrastructure, such as a mobile phone network, that produces entries in locational logs. Active prints come from the users themselves when they expose locational data in photos, messages, and sensor measurements. In [18] for example, geo-tagged crowd-sourced pictures where used to understand the dynamics of flows of tourists in Rome. Another example can be found in [19].

Dealing with cities' dynamics, it is also fundamental to discuss about the City Guide to Copenhagen project [20] which has the aim of designing, visualizing, and presenting innovative applications for mobility, with particular emphasis on parking infrastructure, multimodal transportation solutions, and methods to enhance the experience of using public transport in Copenhagen. Another important aspect could be to change human habits by improving alternative services (bike, trains, etc) thanks to the use of data. Sensors for real time parking availability are in a real time contact with a mobile application to give information to the bikers like health, suggested path to reach the place and other tools. The advantage: providing services to the users, and get information from them.

Related to the city space, not only the human activity is important, but also the quality of life and the conditions of air pollution, recognized as the world' s largest environmental and human health threat[21]. By merging different data, from air pollution data and UGDs, it was possible to quantify the exposure of people to the most polluted areas. Evaluating population's exposure to air pollution using spatiotemporal mobility patterns, warrants consideration in future environmental epidemiological studies linking air quality and human health.

From the above emerged that the use of data collected from humans' activity, monitored through different kinds of connections and technologies, is possible to embrace an incredible number of domains (tourism, urban planning, environmental monitoring) and to address different needs (contextual services, planning criterion establishment, hazards identification). Until now, only the outdoor settings have been discussed. But of course, also an indoor scenario is able to become *Senseable*, likewise analyzing similar dynamics, with similar solution but with a different architecture. While in outdoor the amount of data is at a global scale, and it can reach almost every user with global positioning services, dealing with indoor cases means to built up ad-hoc solutions, even if standardized, to address the task of providing and collecting data from the users. Like in the case of Louvre museum [22] , where an ad-hoc WSN based on Bluetooth radio signal was installed for the monitoring of visitors inside the museum. The main reason of this study was the so-called "hypercongestion", wherein the number of visitors exceeds the capacity of the physical space of the museum. This can potentially be detrimental to the quality of visitors' experiences, through disturbance by the behavior and presence of other visitors. Although this situation can be mitigated by managing visitors' flow between spaces, a detailed analysis of visitor movement is required to realize fully and apply a proper solution to the problem. This problem of movement and circulation patterns in museums was already recognized in the literature as an important topic for research [23]. The use of large-scale datasets enables museums managers to discover and analyze frequent patterns in human activities. Such analyses have been conducted in the specific spatio-temporal range. A Bluetooth proximity-detection approach to the analysis of visitor behavior in museums has many advantages. Contrary to the granular mobile-phone tracking, the detecting scale using Bluetooth is much more fine grained. In addition, in contrast to RFID tags and active mobile-phone tracking with or without, with Bluetooth previous registration is not required and it is not necessary to attach any devices or tags. Moreover, also other features of the behavior of the long-stay and short-stay visitors, including the path sequence length and the unique nodes visited were derived. Visitors' paths and their variations are quite selective, with visitors mostly choosing the same paths in terms of sequence, length and sequential order. Although many other options exist, all these information are needful to improve the museum layout and eventually intervene in a more reliable and efficient way.

The analysis of the works by the Senseable City lab demonstrates that this research topic is emerging and could bring its benefits in almost every domain in which the planning process is required. Notwithstanding, the efforts backed to provide and obtain data, are joint by a fundamental action: to measure. We witnessed to the tremendous growth of localization, even thought with different methods and aims. But localize means measure. Moreover, the main task demanded to a *Senseable Space*, is to measure a certain event and, if possible, to react on it through the provisioning of services to the user. Obviously, those actions are possible just with the use of data, measured data. And it is exactly in this dichotomy that geomatics plays a pivotal role, the science of collecting and providing data, that, in turns, have been measured as well. In the following, a brief dissertation about the "new" meaning of geomatics will be given: geomatics as a fundamental source of data.

1.3 Geomatics: a fundamental source of data

We have described, up to know, the new possibilities offered by devices, sensors and technologies to *sense* the environment; the data exchange among the user and the space proved to be a winning solution for several domains: urban planning, indoor spaces (e.g. museums), geography, retail and many more. We also described some of the services that can be provided to the user according to their location. However, the service for the users cannot be seen just like a notification in a phone or just the number of visitor of a space. The services for the users come from data that they can: interact with, manage and that can improve their knowledge about that specific space. To provide users with contents, there is the need to collect information, from different data sources, and to present them in the right form to be managed. Taking into account the introductory statement that a *Senseable Space* is such, just if we are able to measure it, alongwith the changing dynamics in it, the applied science which brings a strong contribution in this direction is geomatics. A revolutionary turning point about the concept of geomatics was brought by the research paper titled "Geomatics and the new Cyber-Infrastructure" [24]. Authors state that geomatics deals with multi-resolution geospatial and spatio-temporal information for all kinds of scientific, engineering and administrative applications.

This sentence can be summarized as follows: geomatics is far from the concept of simply measuring distances and angles. A few decades ago, surveying technology and engineering involved only distance and angle measurements and their reduction to geodetic networks for cadastral and topographical mapping applications. Survey triangulation, trilateration and even precise levelling have now largely been replaced by Global Positioning System (GPS) applications for positioning and navigation in various modes of implementation. Satellite imagery of various types and specifications are becoming available globally in near real-time for environmental and related applications. Multi-resolution geospatial data (and metadata) refer to the observations and/or measurements at multiple scalar, spectral and temporal resolutions, such as digital imagery at various pixel sizes and spectral bands which can provide different seasonal coverages. Surveying still plays a leading technological role, but it has evolved in new forms: positioning and navigation can be obtained with several devices that were not properly conceived to accomplish these tasks; topographical mapping, one time conducted with bulky instruments requiring complex computation made by the workers, has now become a byproduct of Geospatial or Geographical Information Systems (GIS); digital images, obtained with different sensors (from satellite images to smartphones), can be used to accomplish both the tasks of classifying the environment or make a virtual reconstruction. Survey networks and photogrammetric adjustment computations have largely been replaced by more sophisticated digital processing with adaptive designs and implementations, or ready to use equipments like Terrestrial Laser Scanners (TLS). The transition from analogue to digital methodologies, moreover, has not only resulted from the availability of ubiquitous computers, but has shown to be superior in just about every aspect of data processing and information extraction and identification. Furthermore, as in many other fields of endeavour, computation is now regarded as a primary driver of innovation.

This scenario makes it clear that the digitalization of information enables a rapid and wide dissemination of knowledge, increasing the number of people that can have access to data, improving the sharing and enhancing the quality and the accuracy of the knowledge itself [25]. Moreover, the actual amount of sensors and measuring systems of physical and environmental phenomena allows us to talk easily about "Space Sensing" as a widespread and pervasive approach to understanding the dynamics of the contemporary environments (both indoor and outdoor). What is still missing is the possibility to provide the user with these data in a complete form, and more, how the physical conformation of the space can be changed from the information extracted from it.

A huge help can be exploited from geomatics applications, which are able to cover different working scales [26], as well as to produce different outcomes that are useful for the whole meaning of a *Senseable Space*. Analysis tasks can be performed at a regional level thanks to the use of high resolution images from satellite or aerial images; inferring information is possible thanks to land usage classification [27], as well describing the shape thanks to ranging techniques like LiDAR and Radar pulse. Dealing with architectural scale complex objects, the possibilities offered by new acquisition devices are wide. Low cost equipments (i.e. cameras, small drones, depth sensors, and so on) are capable to accomplish reconstructions tasks. Of course, there is also the accuracy issue to take into account; in fact, geo-referencing complex models requires more sophisticate and accurate data sources like GNSS (Global Navigation Satellite System) receiver or TLS. In the case of small objects or artefacts, terrestrial imagery and close range data are the best solution to obtain detailed information about them. Thus, since we live in an almost well connected digital world, geomatics can play a new role in research and development involving geospatial and related information, as well as creating entrepreneurial opportunities.

The following are listed some potential areas of application that are closely related to geomatics, emerged from the previous analysis: natural environment, quality of life in rural and urban environments, predicting, protecting against and recovering from natural and human disasters, archaeological sites documentation and preservation, just to mention some. We can summarize that geomatics is able to cover the spectrum of almost every scale; even though there is no panacea, the integration of all these data and techniques is definitely the best solution for 3D surveying, positioning and feature extraction. This concept will become more clear in the Chapter 3, where the set of scenarios described demonstrates that the winning solution for the different domain is the merging of data from different sources. Data fusion, or data integration, refers to the process of merging data (and knowledge) coming from different sources (or sensors) - and, generally, at different geometric resolution - but representing the same real-world object in order to produce a consistent, accurate and useful representation. Data fusion processes are often categorized as low, intermediate or high, depending on the processing stage at which fusion takes place. Low level data fusion combines several sources of raw data to produce new raw data. The expectation is that fused data is more informative and synthetic than the original inputs [28].

As well, data visualization has to be considered a core step of the system. If, for example, we are dealing with environmental monitoring tasks, the starting point is a map, obtained with well established processes. From it, it is possible to infer information and extract knowledge of a large scale territory. And, it can also be managed into a GIS environment to add (meta)data to it. However, the map can be fully exploited directly on site, where the operator have the possibility to perform his task with the help of the real environment. The task of the *Senseable Space* is to provide this information to the operator in real time, for instance with his own mobile device. But it is not enough; for completing the system, it is necessary that the user is able to visualize the map, to update its own information, and in the meanwhile to be monitored in his task (for instance by using his Digital Footprints), so that the bidirectional process of providing/getting information can be accomplished. The same example can be done for indoor spaces. If we imagine a space where some sensors (e.g. beacons) are able to track people movement, one of the main task delegated to geomatics is to perform his/her geo-location into the WSN built. If we know the position of this user (e.g. visitor in the case of a museum, a customer in the case of a retail mall), we can provide him with contextual information. These information are always asked to be produced with geomatics techniques (3D reconstructions for instance), that need both acquisition and computation tasks to be visualized in the proper way. Finally, the knowledge of the visitor path provides useful insights to re-arrange the space, if, for instance, some of these data are not visualized or some areas are not visited.

The ones given above are just few examples of how spatial data are a fundamental component of a *Senseable Space*. All the scenarios that will be detailed in Chapter 3 move in this direction; a multidisciplinary work, experienced in different domains, with the main thread of providing/extracting data, with the user at the center, computer science as the link, and geomatics as the mean.

Chapter 2

Augmented Reality tools and applications.

The concept of "augmentation" outlined in Chapter 1 put in evidence the need to mesh-up two dimensional layers (the physical and the virtual) into a single one. It was also described how an augmented space can become a *Senseable Space*, thanks to the use of sensors and services which make our devices able to sense the environment, to get information from the users and give back them services accordingly. We can sum up the above into 3 steps: sense, get and give. Augmented Reality, briefly known as AR, provides these three services. Mainly in the last years has had an increasing importance as growing technology in the field of Computer Vision and Mobile Computing. The main ability of AR is to add virtual objects in real world, enhancing the experience of the users with the reality. According to [29], AR completes reality without completely replacing it. So, it helps users to feel, see and hear better, increasing their perception [30], through the addition of virtual objects and images. Consequently, AR can be potentially applied to all senses (hearing, touch and smell), enhancing sensory experiences through computer-generated contents and eventually other sensory digital inputs with the purpose of increasing knowledge about our surroundings. Taking into account the work of [31], an AR system has the following characteristics: i) to combine real world and virtual objects, ii) to run in real-time, and iii) to allow the interaction between the users and virtual objects [32]. Given these definitions, it is simple to deduce that AR can be used (and useful) for almost every domain of research. Medicine [33], maintenance [34]), environmental monitoring [35], retail are just few examples of topics where AR has been largely adopted [36].

AR have been the main focus of this research; the main purpose, was providing contextual information to the user with a technology that is not well established at all so far. Among the others, CH is probably the one who mostly benefits from the use of this technology. In fact, thanks to the use of AR, users are enabled for a completely new way of experiencing cultural goods. However, even if the literature provides a plethora of new application grown in the last decade with the purpose of enhancing the perception of artworks with digital contents and new way of interaction, up to now there is not an available literature review collecting the main novelties in this field. During the studies conducted by he authors, emerges a lack of a survey able to summarize the main works of AR in the CH domain and demonstrating important research problems or future directions.

Although the multidisciplinary nature of this work brought to uncover the potential of this technology among different domains, as stated in the introduction section, the major efforts were undertaken towards the CH domain. A systematic literature review (SLR) was performed in order to understand the research issues related to the use of AR for CH, and more, to understand if and how this technology could help the creation of a *Senseable Space* in the CH panorama. That is to say, how AR can improve the fruition of the CH sites like museums, archaeological sites and so on?

In the following, besides a brief overview about AR definitions and enabling technologies, a specific focus on the CH panorama is presented, with the definition of a taxonomy created according to the SLR performed.

2.1 Background

Mainly since 2001, AR became an important area of research for CH when it was for the first time applied [37]. CH domain witnessed to a crucial turning point in the way in which art is experienced by the users. Research has increasingly focused on emergent technologies and mediums to improve the digitization of CH. Speed up in innovation is strictly related to several aspects, being technological and anthropological. Mobile devices are increasing their popularity among people as well as the significant development of user modelling and personalization processes which places the user at the center of the learning process. AR is a valid technology able to virtually reconstruct destroyed monument and historical building, enhancing the experience of users when they visit ruined cultural heritage sites [38]. In education, AR systems represent a platform of learning, motivating and understanding of events and historical elements for the students and researchers. The importance of virtual restitution of historical sites is to preserve, protect and interpret our culture and history. In [39], the authors indicated in seven points the importance of AR applications applied to CH.

In recent years, CH domain witnessed to a crucial turning point in the way in which art is experienced by the users. Research has increasingly focused on emergent technologies and innovations (e.g. virtual learning environments) to improve the digitization of CH. Devices can sense the environment (and the user location) thanks to the growing enhancement of built-in sensors. The ability to provide visitors with digital services is a key aspect to make spaces more accessible [40], interactive and enjoyable. AR is able to deliver these services, since it gives the possibility to overlay virtual information about physical objects directly above the device' s screen. AR browsers have great potential to improve way-finding and context-awareness services for users. This aspect is taking a strong impact even in the world of CH. Insiders, archaeologists, scientists, researchers wonder how to make more appealing museums, their exhibition areas, their heritage and so on. In [41], the authors propose an efficient system able to guide visitors using informative contents related to the exhibition. The major contribution of their proposal is the ability to integrate a standard solution with multimedia services. Moreover, to create a narrative process enhanced by multimedia cultural resources, digital storytelling has an important role since exploits these digital tools for editing and increasing the diffusion of contents [42].

This was made possible thanks to the enhancement by [43], [44], because they increase computational capabilities, sensor equipment and the advancement of 3D accelerated graphics technologies for hand-held devices. For these reasons, they are relevant example to be mentioned. In general, AR applications have been also developed for archaeological settings. For example, considering recent works [45], historical and archaeological aspects are combined to obtain a most real environment where the archaeological ruins are arranged with the ancient landscape. Another recent AR application for archaeological sites is known as ARAC Maps Eggert [46], where the aim is to enhance archaeological maps combining 3D models with other possible interactive approaches. There are other approaches, much more simple, that do not use particular hardware devices. In these kind of applications, where an example is described in [47], the innovative aspect is the ability to show the virtual reconstruction on a real context with an immediate dimensional and spatial feedback.

In general, the projects that involve AR applied to architecture, landscape and archaeology (and more in general to CH) are developed by a team of specialists in different disciplines that allows a responsible and efficient use of Information and Communication Technologies (ICT) and computer-mediated reality in knowledge-based experiences [48]. The introduction of innovative digital tools has the aim to provide users, with different skills, with useful instruments for the knowledge and dissemination of artistic and architectural heritage.

2.2 Enabling Technologies

Experiencing AR application is related to a set of choices that, during the design phase, one has to take into account, in order to provide the user with the best solution. There are several important aspects for creating appropriate experiences, allowing the end users to interact with virtual contents in an intuitive way. These aspects can be summarized in three main components: first of all, the tracking system, which represents the core aspect in order to make the device able to interpret the environment. Secondly, the choice of the development framework, whose choice is generally oriented among free or commercial platforms, besides the tracking technology they are able to provide. Last but not least, the system and devices that are chosen for the experience; hand held or head mounted devices implies several decisions to undertake. Even if this dissertation is more oriented towards the Cultural Heritage panorama, it is worthwhile to give the reader an overview of the state of art systems and enabling technologies. Referring to the considered period of this study, the first important review about AR system can be dated back to 2008 [49]; in order to establish the geometrical relationship between the user's viewpoint, the display, and the environment many technologies can be used. Widely used in the CH frame are based on vision [50] and sensors [51] tracking. These approaches are used to display virtual contents properly registered within the environment. To maintain frame coherency between the content and the camera, there is a need of continuous tracking. In the following, these aspects are showed in detail with different use cases.

2.2.1 Tracking systems

Detection, tracking and pose estimation. These are the main steps that a device performs in order to superimpose the virtual object co-existing with the real scene. Tracking, or camera pose determination, is the main technical challenge in creating AR experiences. As discussed in the following section, the main purpose of using AR in CH is to communicate a cultural good, or a cultural place, through the use of a device. The augmentation of them is related to the way in which programmers enable the device to recognize the scene, hence, the proper tracking system is required. For instance, if we move in outdoor environment and we want to drive the user into an unfamiliar environment like an archaeological site, the use of the GPS, compass and gyroscope is necessary to retrieve his/her location. See [52] for a good explanation on how the registration step can be achieved. On the contrary, when we are inside a museum, there are countless features that can be recognized by a camera but a lack of connectivity, so that the use of vision approaches is preferred. Camera-based techniques, have become increasingly popular due to their cost-effectiveness and availability in commercial products (such as portable computers and mobile phones), that can serve as *video see-through* display.

2.2.1.1 Vision-Based tracking systems

Vision-based tracking (also called *marker-less*) techniques make use of image processing methods to calculate the camera pose relative to real world objects. In computer vision, most of the available tracking techniques can be divided into two classes: *feature-based* [53] and *model-based* [54]. The underlying concept of *feature-based* methods is to find a correspondence between 2D image features and their 3D world frame coordinates. The camera pose can then be found from projecting the 3D coordinates of the feature into the observed 2D image coordinates and minimizing the distance to their corresponding 2D features [55], [56]. *Model-based* techniques, instead, explicitly use a model of the features of tracked objects such as a CAD model or 2D template of the object based on the distinguishable features. The tracking phase is based on lines, edges or shapes present in the model. Edges are the most frequently used features as they are computationally efficient to find and robust to changes of lighting. A popular approach is to look for strong gradients in the image around a first estimation of the object pose, without explicitly extracting the contours [57]. Given the analysis of works related to the CH domain, *vision-based* solutions are the most used. For indoor environment in-fact, the use of GPS solutions is not allowed, and the ability of a device to sense the environment is limited to the built-in camera. The use of wireless connectivity is typically required for outdoor situations.

2.2.1.2 Sensor-Based tracking systems

Performing AR in outdoor scenarios, where lighting condition and the variety of landscape hamper an affordable use of *marker-less* solutions based on image matching, requires the use of the so called *sensor-based* tracking. These techniques deal with the registration of virtual objects in the camera scene, based on the user's location and orientation. To determine this, the device makes use of GPS receiver to retrieve the user's location in the real world, and of gyroscope and compass to get the user's orientation. Hints about this techniques are reported in [51]. In other words, the system rely on (geo)location services to determine the distance between the user and the Points of Interest (POIs) that are present on the surroundings. As discussed in [58], Public Open Spaces (POS) like parks or archaeological areas might have countless objects to be highlighted. And the closer the user is, the higher will be the error, caused by a deficiency of the receiver in terms of accuracy. This aspect will be emphasized in the Chapter 4, but it is demonstrated by several works that the possibilities offered by this system are enormous, especially for tourism and business purposes [59]. Up to now, there are not robust and affordable solutions for indoor localization able to provide a stable definition of POIs to be showed in AR.

2.2.1.3 Hybrid tracking systems

From the above emerges that there is not an existing solution able to embrace all the needs in every conditions. In fact, depending on the needs, for some AR applications, computer vision alone cannot provide a robust tracking solution. That is the reason why during the years hybrid methods have been developed combining several sensing technologies (namely *hybrid*). Very interesting is the work proposed by [60]. In their work, authors propose the use of Kinect to establish 3D world and 2D image correspondences and, from them, determine camera pose. It is known that by introducing the depth contribution to track the scene, the registration of the object can be improved in terms of accuracy and occlusions can be managed. Most in general, the trend is to combine simultaneously GPS and optical tracking, which is a really good solution in those cases where the POIs are very close to each other (e.g. in a big city). With the help of the picture taken by the camera and the GPS coordinates, the device could recognize the attractions in a more simple and reliable way [61]. Despite the current weakness of the technology, the rapid development of mobile technology anticipates that *hybrid* technology is the future of AR.

2.2.2 AR Development tools

The current status of available development tools depict an emerging growth area. There have been a number of software frameworks created to support AR development. This section provides an overview of some of the more suitable ones to be used for the CH domain, tested and verified by the authors during their research work. The first discriminant is the choice of the Operative System (OS). This is not trivial, since not all the available frameworks are suitable for the most widely adopted OS (Android and iOS); however, to reach the majority of the users, the platform has to be taken into account in advance. Even if the number of tools is day by day increasing according to the literature review performed, the following are the most commonly used frameworks: Wikitude [1], Layar[2] and Vuforia[3] are commercial, PanicAR[4], DroidAR[5] and ARToolkit[6] are free. Wikitude is a commercial framework released in 2008 which exploits both *location-based* and *vision-based* tracking. For the description of the use of this framework in a museum environment see [62]. Layar is the most widely solution for *location-based* services. The possibility to store the POIs in a remote Data Base (DB) and to retrieve their information according to the user

[1] http://www.wikitude.com
[2] https://www.layar.com
[3] https://www.vuforia.com
[4] http://www.panicar.dopanic.com
[5] https://bitstars.github.io/droidar/
[6] https://artoolkit.org

location make this framework particularly suitable for outdoor way-finding experiences [63]. After the removal from the market of Metaio, that for years was the most powerful tools to develop *vision-based* AR applications, Vuforia has become the choice for the vast majority of developers. In [64] authors present a framework for the visualization of 3D artefacts in archaeological contexts. Its integration with Unity3D fits with the needs of a proper visualization of 3D models, besides a fast and easy cross-platform development. It supports a variety of 2D and 3D target types including Image Targets, 3D Multi-Target configurations, and a form of addressable Fiduciary Marker known as a Frame Marker. Additional features of the SDK include localized Occlusion Detection using "Virtual Buttons", runtime image target selection, and the ability to create and reconfigure target sets programmatically at runtime. Moving on free or open source solutions, Artoolkit is an open source *vision-based* AR library including features such as: camera position/orientation tracking, easy camera calibration code, cross-platform development. Distributed with complete source code, it was initially designed to run on personal computers, so that porting into mobile devices SDK is quite impervious. PanicAR, distributed with free licence, is specifically designed for iOS development and it is based sensors tracking. The work described in [65] shows the use of *location-based* AR to enhance the tourism experience in outdoor scenario. Finally, DroidAR was implemented to create AR application for Android OS with both location and vision based approach. It has great potential since the source code is available, but the implementation is still from two years. A test conducted with this tool can be consulted in [66]. From our tests, Vuforia provides tracking system that is more reliable in terms of rapidity and stability, while for outdoor scenario Layar is the most challenging framework, especially in terms of accuracy. In the Table 2.2.2 is presented an explanatory report, showing features and weakness points of the presented tools.

Table 2.1: Comparison between the most commonly adopted frameworks in the field of DCH, divided in free and commercial to be adopted for both indoor and outdoor scenario

SDK	Purpose	Tracking	OS	Graphics	Cloud	Sensors	License
Wikitude	Indoor, Outdoor	Location-Based, Vision-Based, 3D Tracking	iOS, Android	3DUnity 2D images, text, 3D Models	yes	GPS, IMU	free and non-free
Layar	Mainly Outdoor	Location-Based	iOS, Android	2D images 3D models	yes	GPS, IMU	non-free
Vuforia	Indoor	Vision-Based, 3D tracking	iOS, Android	3DUnity, OpenGL 3D models	yes	GPS, IMU	free and non-free
PanicAR	Outdoor	Location-Based	iOS	2DImaged Labels	no	GPS, IMU	free
DroiAR	Outdoor	Location-Based	Android	2D Images Labels	no	GPS, IMU	free
ARToolKit	2Dimages, Markers	NFT, Markers	iOS, Android	3DUnity, Android	no	no	GPL

2.2.3 Systems and devices

To obtain the result of augmenting the user's perception of the real world, AR deals with the enhancement, rather than the replacement, of the environment. Since a camera is one of the core component of the system (see Section 2.2), the most common solution in the CH is the use of Hand-Held Devices (HHD), generally mobile phones or tablets. However, in the last few years, we witnessed to the growing of commercially available Head-Mounted Devices (HMD). Even if is not the purpose of this dissertation of giving technical details about this kind of solutions, some examples will be mentioned. HMD can be divided into two main typologies: *optical-see through* and *video-see through*. See [67] for in-depth analysis. The first once, projects the computer generated data over a semi-transparent screen through which the user continues a seamless contact with the reality. For the CH domain, the work by [68] is a good example to be mentioned. Referring to commercial devices, among the others, the latest version of Hololens by Microsoft demonstrated to be the most promising head-set, since includes into the same device *vision-based* recognition with the addition of depth-sensors to sense the environment also with the help of the third dimension. Similar application with a prototype realized to experience heritage site in outdoor conditions can be found in [62].
The second rely on the camera stream with the same point of view of the user. These last are the most widely adopted for the CH domain, since the hardware and software components are similar to common mobile devices, simplifying the development process. After the disappearing of Google Glasses from the market, Vusix and Moverio by Epson are the widely spread. Nevertheless, the use of HMD for CH purposes is still in its infancy, as discussed in the user test reported in [69]. Actually, rather than research projects or application in this direction, we can find only ad-hoc installation using Smart Glasses [7] to discover ancient buildings or places. One of the latest experiences to be mentioned is the Aracomera project[8], where the famous Ara Pacis in Rome is bring to live through an exiting storytelling application, experienced using AR HMDs.

2.3 Taxonomy of applications for the Cultural Heritage domain

By and large, cultural heritage sites, goods and artefacts get a significant added value from their enrichment through digital means. Notwithstanding, many art curators still believe that the use of technology will place art in background

[7] http://www.art-glass.it. Art Glasses is an Italian leading company that realized several project using HMDs

[8] http://www.arapacis.it/mostre_ed_eventi/eventi/l_ara_com_era

[70]. This is mainly due to different aspects, that can be summarized as cultural and generational. First of all, there is a widespread scepticism from the so called “not digital naive” in using mobile technologies. Secondly, and most important, is related to the way in which technology is used. The trend in using multimedia application is more oriented towards the “show” of innovation, rather than using digital tools to solve specific problems [71]. However, there is general agreement that the use of visual CH tools meant for non-technical users (who are still not very skilled in multimedia technologies) is an important factor for their success [72]. For the enhancement of CH fruition, researchers’ efforts are oriented towards providing users - insiders as well as non expert public - with new instruments for the knowledge and dissemination of artistic heritage. This approach is carrying successful influence, for example increasing the interest of young people by means of new tools. Generally, museums installations that do not introduce new technologies, are often boring and do not always have the reputation of being attractive [41]. Furthermore, learning experiences in museums have been facilitated only by the use of labels and descriptions, which are informative but not interactive [73]. The creation of an intelligent environment, which is responsive to the human presence, dynamic and mobile oriented would make the visit path more appealing, bringing new avenues to the CH domain [1]. Augmented Reality systems proved to be valuable solution, representing a stimulating opportunity that allows navigating, interacting and discovering different setting, with several purposes. In archaeological settings for example, the problem of the dissemination of heritage is mainly related to the need of communicating goods that are seriously damaged of, more often, that are definitively lost. AR could serve as an X-Ray application to discover what is concealed under the ground, or to augment the environment with virtual reconstruction of a lost heritage [74].

From the above, arose the need of making a classification of Cultural Heritage sub-areas, in order to understand where AR can be a successful solution and which kind of tracking system should be used according to the different scenarios. In the following, a taxonomy is proposed, built up following the findings of this literature review; in fact, during our research, the following topics seems to be the sub-areas in which AR has been used: *Archaeology*, *Museums*, *Tourism*, *Restoration*, *Learning*.

2.3.1 Archaeology

AR has a strong potential in the archaeology domain. Several studies have been conducted in order to evaluate the state of art within this discipline [75], [76]. Besides, the impact of using AR in archaeological settings have been evaluated

in terms of users acceptance [63]. The possibility of enriching the reality with computer generated information, providing innovative ways of information access at CH sites, has been experience in several research works. In [77] for instance, authors describe the visualization of a part of the Middle Stoa in the Ancient Agora of Athens; users have the opportunity to see how this building looked like in ancient times, as its three dimensional model is displayed on the camera view of their device, projected on the modern-day ruins. Similar examples can also be found in [78] and [79]. The need to discover ancient artefact is expressed in other cases, with specific implementations to experience contents also in indoor scenario. In [80] in fact, virtual reconstructions are showed in both indoor and outdoor scenario, using different tracking technologies for the same purpose. A more complex framework to facilitate the access to the information can be found in [81], while the work of Empler shows good quality models visualised in AR [82]. And more, ARcube system [83] is noteworthy, since a low-cost and automated method for a flexible management of virtual goods is proposed to be beneficial to public research (e.g., museum exhibits) and education (e.g., the classroom).
From this brief analysis, three main points arises: first of all, the possibility to use AR application is strictly related to the use of the so called *sensor-based* AR (see Section 2.2.1), while the interaction with virtual archaeological contents into museums is not spread so far. Second, AR is mainly used to visualize lost artefacts or conceived ones. Third, the use of geomatics applications in archaeology is unavoidable. This last concept was pioneered some years ago [84]. Virtual reconstructions in fact, can only rely on accurate reconstructions, realized thanks to the use of different data sources [85], [66]. Making this experiences more attractive for the users is also related to the possibility to interact with contents, making them more active in the learning process. Examples of well developed and thorough interactions by the users with mobile applications have been developed by [86] and [87]. In the last decade, archaeology can benefit from an incredible availability of digital 3D models, which represents a means of communication and dissemination [88], allowing also to reach impervious environments like in underwater conditions [89]. The challenge, that will be exhaustively described in the discussion section is twofold: on the one hand, describing a known work-flow that brings from the data acquisition to the visualization in AR fashion environment. On the other, making these data portable and multi-purpose to be exploited in different devices or platforms.

2.3.2 Musealization

Visitors involvement within a museum installation is necessary. Moreover, the mediation between the traditional approach and the clever use of new media is mandatory [90]. Whether AR in archaeological settings seems to fit with the needs of such domain, also in indoor spaces the use of this technology has proved to be a valuable solution. The number, and the quality, of applied research papers in this field is high, since AR can provide a variety of solutions to help museums fulfil their role and goals [91]. Dating back of some years, the use of AR was mainly proposed as a support in the guidance of users inside museums. The trend was attempting to solve the specific problem of assisting the experience design issues related to museum visits. In [92], an audio AR and tangible user interface system was developed. Authors explored the possibility of supporting a context-aware adaptive system by linking environment, interaction objects and users at an abstract semantic level instead of at the content level. Other solutions were proposed following this need also in [93] and [94]. Even if a complete route guidance of the museum space was never implemented at all, there have been several attempts to enrich the visit quality by the use of AR, also in real case permanent exhibitions. The paper by Odzen et. al. [95] presents user interaction modules of two important museums: Istanbul Archeology Museum and the Museum of Dolmabahçe Palace Collections in Istanbul. Another real case can be found in [96], where the user experience was made more immersive, engaging, and interactive at the Herbert Museum and Art Gallery. It is known that one of the main issue for the art curators is the possibility to show the entire museum collection, mainly due to space issues [97]. A good dissertation about a visualization taxonomy can be found in [98]. The system proposed in [99] delivers a guidance with intuitive and user-friendly interactions between man and machine based on computer vision technique in ubiquitous computing environment. The system is able to display and illustrate contextual information about 3D models of museum artifacts and multimedia materials to users in real time to compliment the museum experience. The interesting solution of combining hologram techniques and AR was also testes, with the results showed in [100].

Regardless the type of installation chosen in the different case study presented, it is proved that the level of interest of the visitors grows when such solutions are delivered [101]. Since the use of mobile devices is increasing also for cultural and museum sectors, the number of apps available on the main stores (e.g. Google Play, Apple Store) is daily growing and many Museums Apps are noteworthy. A good survey over this kind of application, as well as over the impact of mobile devices in terms of app development can be found in [102]. Also in the Italian National panorama this trend is strengthening, as demonstrated by the increasing number of mobile apps available in the stores[9]. Many aspects have to be taken into account developing a mobile app; planning and production of cultural content for mobile usage should respect the synergy

[9]http://www.beniculturali.it/App

between digital contents and usability. Furthermore, proper planning of the steps development are mandatory. An helpful dissertation over mobile development for CH can be found in [103]. The potential of AR have been more exploited through Mobile Augmented Reality (MAR). The reason of this is twofold. Firstly, mobile devices are widespread, making the diffusion of ad-hoc application more simple. Furthermore, with the advent of performing devices and of novel solution of image matching algorithms [104], the usability and the quality of MAR apps grown tremendously. Literature provides many relevant works about using AR mobile application for CH purposes [105]. The discussion backed by [106] about the use of marked or *marker-less* AR (see Section 2.2) have increased meaning when we talk about museums and more in deep about artworks. Since one decade ago, the use of marker-less solution was not supported by an agile development, requiring difficult attempts that impede the vast diffusion of this solution [107]. The alternative was the use of QR code, that of course represent a not appealing solution in front of works of arts. Nowadays, the possibility to get virtual information overlayed above a screen simply by framing a painting reached remarkable results. In [108], a painted architecture by Paolo Veronese was bring to live thanks to a 3D reconstruction, while in [109] and [50] the famous painting “La Città Ideale” was augmented through digital information without artificial marker, as described by different case studies in Chapter 3

2.3.3 Tourism

The potential of mobile devices is growing with impressive speed, changing the way in which tourists gather and access information, especially in outdoor environments. And more, the worldwide adoption of mobile devices by the users can replace traditional orientation, guides and way-finding maps, moving towards the exploitation of built-in sensors of modern mobile devices. This is mainly because cameras, GPS sensors and Internet connection open the way towards a new manner of experiencing public spaces, thanks to contextual information. With context-awareness services tourists have access to interactive experiences and, even if with little knowledge of a certain area, they can naturally experience unfamiliar places. A relevant research is presented in [110], which shows an interesting case of exploration of buildings in urban settings; the study outlines design recommendations that should be considered by future generations of *location-based* AR browsers, 3D tourist guides, or in situated urban planning. In [111] an outdoor AR experience based on markers was developed, but it is quite obvious that AR represents a natural choice for exploring (geo)information of real world objects, mainly because they can be superimposed onto the display, with the same point of view of the user. A good "vademecum" of the challenges that developers have to take into account when designing AR browsers for outdoor environments are discussed in [112] and [113]. In [114], a specific application was designed to allow people downloading contents related to the CH area they were discovering. From the e-learning standing point, MAR has proved to be a winning solution [78]. However, some technological and anthropological issues still exist, preventing MAR from becoming a broadly used tool for open spaces. External variables that influence user acceptance include enjoyment, personal innovativeness, perceived benefits, costs and information quality [115]. Current issues and benefits of using AR for tourism purposes are widely discussed in [65]. In [116] interesting consideration has been done, with respect to the criteria that should be used when developing an AR service for tourism. Four features should be followed: readability, unambiguous association, aesthetics, frame-coherency. CorfuAR [117] is a tourist city guide using the strengths of the AR technology, by placing digital information about surroundings upon the screen of the device. The experience of visiting Corfu is enhanced with virtual information about sights, museums, monuments, religious sites, nature and many more. PRISMA project [118] had the aim of enriching the real scene with interactive multimedia information and of increasing the tourist's experience, who can retrieve this information from a user-friendly interface. In [119] a prototype to increase tourism has been developed and reviewed by two focus groups on the campus of Fu-Jen Catholic University. AR provides hidden information of the campus in the area, providing students with immediate assistance in case of loosing and also representing a mobile learning tool. Lecce AR[10] [120] is another interesting example of visualisation of 3D models during a visit for city environment. It allows adding to a real-world scene, seen from a mobile device's camera, with 3D models of CH sites as they looked in the past. 3D models are displayed when the user points the device's camera towards a planar target which can be a photograph or an image. The experiences of using AR as POI finder was experienced and it now represents a state of art approach [121], [122]. However, a look forward in the relation between the user, the devices and the space was given in [123]. In [124], using the results of an applied research project "ways2gether: target group specific use of AR and web 2.0 in participative traffic planning processes", authors describe the possibilities of implementing AR in planning and participation processes. The article points out that AR tools expand the repertoire of methods used in participation procedures and that they have the potential to support many phases of a planning and participation process.

[10] http://vcg.isti.cnr.it/LecceAR/

2.3.4 Restoration

Since now, this review outlined different opportunities to facilitate the access to cultural goods and sites, using different approaches. However, AR can also serve as a tool for maintenance and restoration purposes. In fact, many advantages are obtained among which: the manpower and machine power are utilized only in the last phase of the reconstruction; potential damages/abrasions of some parts of the structure are avoided during the cataloguing phase; it is possible to precisely define the forms and dimensions of the eventually missing pieces, etc. Actually the virtual reconstruction/restoration can be even improved taking advantages of the AR, which furnish lots of added informative parameters that can be even fundamental under specific circumstances [125]. To ensure the preservation of artifacts, such as statues or paintings, they must be analysed to diagnose physical frailties that could result in permanent damage. Advancements in digital imaging techniques and computer-aided analysis have greatly improved in such diagnoses but can limit the ability to work directly with the artifact in the field. Even if Virtual Reality (VR) solutions have proved to be more reliable and efficient in this sub-domain, there are some applications of AR to be mentioned. Several examples on different kind of diagnosis are reported in [126]. Very interesting is the work proposed in [127] for the restoration of religious heritage. Authors describe a complete workflow starting from the reconstruction of statues until their visualization in AR in their geo-located position. In [128] the ARtifact method is proposed. It consists in a tablet-based augmented reality system that enables on-site visual analysis. The idea behind this project is to use different layers overlayed above the device's screen, representing images acquired with different data sources. The tools is designed for on-site diagnosis and restoration. Another tool was specifically implemented to distinguish details that are difficult to discover due to ageing effects. The name is the "Revealing Flashlight" [129], that works by projecting an expressive 3D visualization that highlights features, based on an analysis of previously acquired geometry at multiple scales. The novelty mainly lies in the interaction techniques, based on gestures.

2.3.5 Learning and Education

When we deal with CH, every research work related to the dissemination and diffusion can be associated to the learning paradigm. Anyway, besides the works showed in the previous subsection, in the literature is possible to find tools and applications specifically designed with the learning aim [130]. Museum designers might leverage AR' s capacity for spatial and temporal representation, narrative and interactivity, real-time personalized scaffolds, and collaboration, to create meaningful learning experiences. By increasing the sense of place, for instance by improving the visit or the way-finding of an environment, the learning activity can be strongly improved [131]. It is easy to summarize that this approach can be extremely useful by exploiting the augmentation of a museum collection. The test conducted for butterfly's specimens, examined in National Museum of Natural Science in [132], is a confirmation of this. In [133] the theme of playful learning is widely discussed. This approach can cross the boundaries among schools, museums and science centers, by involving the participating (e.g. students) in extended episodes of digital interaction with the exhibition. The results demonstrate that the technology provided significantly improved learning outcomes, increased students curiosity and their willingness to communicate and share their enlightening experiences with other students, their eagerness to use new technologies, and acquire knowledge through having fun and experiencing. Also the work by Invitto et. al [134] goes towards this direction; the authors configured various types of intervention and study related to new technologies and new scientific languages, depending on the objective of learning and involvement. The idea of the work is to increase and to enhance the usability of MAUS Museum through an app of AR and through Virtual Reality projections, related to natural stimuli (Plankton 3D and Tarbosaurus 3D). Another example to improve the learning process into museums through the use of AR can be found in [135]. For architecture, the House of Olbrich house app [136], represents a good case study where AR (location and vision based) was used in order to communicate details and historical information about the building.

Following the taxonomy just described, we developed several pilot projects, described in Chapter 3 (specifically for musealization, archaeological and tourism purposes) where the use of AR was exploited to enhance the users' experiences and to measure humans' movements and behaviours.

Chapter 3

Use cases and results. Applications of Senseable Spaces

As showed in the previous Chapters, the augmentation of the space is entrusted to the ability of developing a bidirectional interaction between the users and the space they live. More in deep, if the user is provided with contextual digital services, he is able to explore the space, to know it, and to get an improved knowledge about his surroundings. But the ubiquitous nature of the devices adopted to exploit these services, allows the manager of the space to collect data from this usage, to understand if the service provided is suitable for the initial purpose and to adjust it by measuring users' insights. The increasing technological deployment is allowing a new approach to gain information about environments, about their changes, about the possibility to predict and anticipate them, as well as to provide users with new tools to interact with augmented spaces. The aim of the research activity conducted during the years of the Ph.D. studies by the author, is oriented towards the use of sensors, devices and technologies able to make the concept of *Senseable Space* real. The goal of understanding the dynamics of a space starting from the knowledge of the users was experienced in different domains of applications. This for two reasons: first of all, even if the main activities where conducted into the CH domain, it was not sufficient to understand the limits and benefits of this paradigm only by exploring a single topic. Secondly, different domains have different needs, so that to understand the potential of *Senseable Spaces*, it was fundamental to face with different scenario and, eventually, to outline points of contact. Following the paradigm of *Senseable Spaces* as the main thread, we selected a set of experiences carried out in different fields; at the center of this investigation there is of course the user, in the double meaning of end-user and manager. Besides, both indoor and outdoor scenario have been explored, since the knowledge of the operational condition of a space is a mandatory requirement to use the technology in the most proper way. The main topics of investigation have been the following: **Cultural Heritage**, described through several applications in both museums and archaeological settings, **Public Open Spaces**, where the core activities where performed within the framework of the European project CyberParks, **Geosciences** through the case study of an ad-hoc application for environmental monitoring and finally **Retail Environments** that, because of its nature of being a pervasive environment, a *Senseable Space* can be built in its whole meaning.

3.1 Senseable Spaces and Digital Cultural Heritage

In the CH valorisation and communication, ICT offer an easier access and a multi-perspective view of artefacts and can also increase education, thanks to the use of innovative learning/teaching methods [137]. Visitors of a museum can interact with the content in the most interesting way thanks to the introduction of ICT. In the last years, many researches have been aimed at providing museums with interfaces and software tools. Their intention is to develop web-based virtual museum devices integrating 3D computer graphics and augmented reality (AR). Sylaiou et al. [138] demonstrate that there is a relationship between a high level of presences and the satisfaction and gratification of visitors, while interacting with a museum simulation system and living a more attractive experience. In the next years, the diffusion of smartphones and the growing use of social networks will bring to an integrating of social, AR applications and digital storytelling. But this is true not only for museum environment but also for archaeological areas. As demonstrated in the systematic literature review presented in Chapter 2 of this thesis, the main contribution from the use of new media can be exploited in both indoor and outdoor settings. The purpose of making a heritage site *Senseable*, can be reached with the twofold approach of giving services to the visitors and collecting their insights to improve the service provided. In this specific domain of course, a fundamental step to provide high quality content is demanded to Geomatics applications. In fact, dealing with complex architectures and spatial data in general, the data collection phase, that seems to be just a preliminary phase, become essential. TLS, Multi-view Stereo (MVS) matching, GPS and other sources are, up to now, well established solutions that could bring a great benefit. However, the management of the quality, as well as the construction of an affordable workflow that ranges from the acquisition to the visualization in a *Senseable Space*, is not totally established so far. The interaction with virtual contents, their visualization in different devices, the ability of devices to sense the environment in order to provide contextual information are all elements that play a pivotal role. And more, since the curators have the need to understand if the services provided are accessible and usable for the users, there is also the necessity to analyze their behaviour for the improvement of these services. Given the above, in the following we show different use cases, selected as the more relevant among the works conducted in the CH domain, experienced for both museums and archaeological settings and demonstrating, in the results sections, how the use of the developed digital tools have increased the value of the scenario where they have been used.

3.1.1 Real case exhibitions in museums environments

Exhibitions are becoming ever more interactive. Museums undertaken the strategy of offering technological services to its visitors; furthermore, insiders are increasing their awareness about the need to provide visitors innovative solution of experiencing art. The spreading of advanced digital tools (e.g. mobile applications, addictive interaction systems and multimedia contents) made possible a new paradigm for art installations. New trends in the international panorama demonstrate how such innovative tools are the best (and only) way to enhance the fruition of CH. Through digital tools, the museum experience becomes a lay experience of culture and then the art seems democratic. The taxonomy proposed in this thesis about the use of AR in different sub-areas of CH demonstrate this trend. Up to now, what is missing, is the real exploitation of the pervasive nature of mobile devices. In fact, so often digital installations require cumbersome equipment that place the user in another dimension (like for instance with the use of Virtual Reality (VR) experiences) and that need skilled staff to train the users to perform the task. Mobile devices and simple interfaces have the capabilities to reach the vast majority of the public, in an interaction that move from a “one to one” to a “one to many” experience. But this is not the only issue. The knowledge of the users‘ insights is needed, if we want the evolution of the digital product itself. The study cases proposed in the following go in this direction. Starting from the famous painting “La città ideale”, we developed, tested and delivered several AR tools that are able to give new hints to the exhibition without the need of further equipments, apart from the device that single visitor have at his disposal. A specific focus was also devoted on the user behaviour understanding, using both classical direct interviews and eye tracking technology.

3.1.1.1 Scenario 1: Augmenting paintings through AR

The usefulness of a *Senseable Museum* is to provide cultural institutions with the best practices of digital interactions efficiently and with low budgets. Hence, this work started with the main objective of developing a low cost method for high-resolution acquisition of paintings that is used as a base of knowledge for the development of an AR application. The case study chosen was the famous painting “La città ideale”, preserved at the “Galleria Nazionale delle Marche” in Urbino. Starting from this experience, the work was extended and installed in a temporary exhibition about Piero della Francesca, that will be detailed in the following. The first problem we faced during the development of the AR application was the lighting condition inside the museum. In fact, artificial lights and protecting glass generate abrupt reflections that generally cause instability during the feature extraction phase (see the enabling technologies discussed in Chapter 2). Experimental results demonstrate the robustness of the proposed approach with extensive use of the AR application in front of the painting. The first step was to obtain a low cost acquisition way for high-resolution images. In order to provide a digital electronic replacement for conventional photography of paintings, several systems were developed in the last years [139]. The acquired image was then used for the development of the mobile application and, later, for the installation described. Users tests in the real scenario were also conducted to prove the usability and ensure a good user experience.

3.1.1.2 System architecture

The first stage of this experience was the development of an AR tool, based on the whole painting image, designed to augment the painting. Once the app is launched, the device's camera is activated and ready to recognize a target (according to the point selection framework described below). When framing a target image, the information pop-up is shown and a button in the action bar becomes active; if pressed, a radar is displayed on the top left of the screen. This feature shows the user the position of the other POIs (see Figure 3.1). Each of these points is represented as a marker and a billboard containing the name of the painting. This system shows the user the direction to follow to reach the painting through AR. For further information on how to reach a point of interest, the user has to only tap the corresponding geometry. This will display the path on the museum map from the current user position to the selected painting.

The meaningful steps for the creation of the Ducale AR experience are the content creation, the web, and the final visualization. This last is the more challenging, since it is related to the lighting issue described above; the proposed methodology for the development of the AR tool consists of an improved SIFT extractor for real time image using a robust matching. The other novelty of this work is the multipoint probabilistic layer. Details about the methodology can be found in [50].

The application was then required to be part of the real case exhibition *PIERO DELLA FRANCESCA. Il disegno tra arte e scienza* [1]. The whole installation system (see Figure 3.2) is composed by a faithful (and real-scale) facsimile of the "Ideal City" painting and a touch-screen. The artwork is flanked

[1] http://www.palazzomagnani.it/2014/11/piero-della-francesca-il-disegno- tra-arte-e-scienza

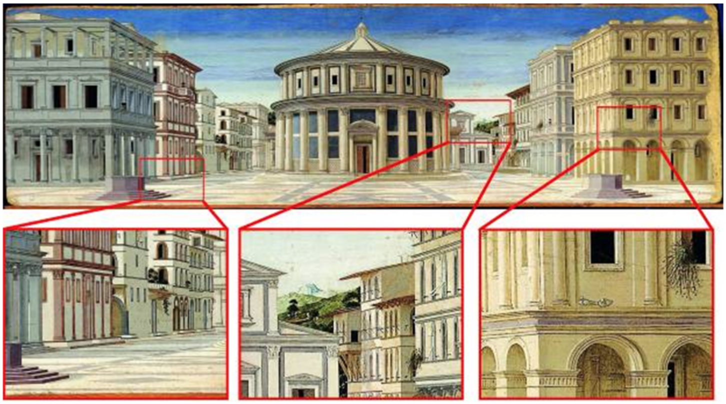


Figure 3.1: The marker less tracking creation.

by tablets which allow visitors to interact with multimedia contents thanks to the applications, already installed; inside the touch-screen the HR image of the painting is installed (refer to Figure 3.2 for a comprehensive overview of the installation). The different "visions" of the same artwork, here accessible,

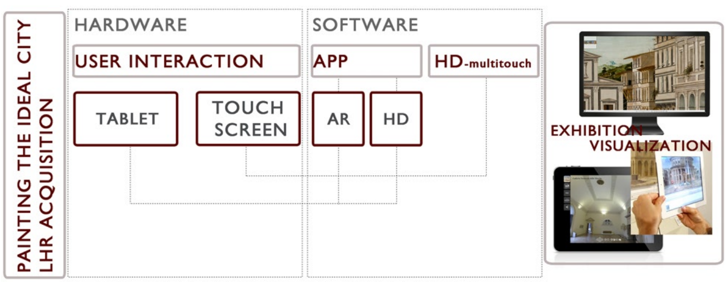


Figure 3.2: Phases and connections between elements: the production chain from the LHR acquisition to the exhibition.

form a new way to communicate paintings and to facilitate its disclosure with edutainment practices. The HD makes more evocative looking at the painting, because it allows to watch it as well as the artist and to enter the will of representation. The "Città Ideale" app facilitates the link with the painting thanks to the technology, but the tool still needs the real art work, in its physical dimension, in a close relationship between art and technology. Details about development and technical issues are discussed below.

In the exhibition it is possible to use a browser to navigate the "Ideal City" macrophotography through a touch-screen. The user can perceive an amplification of the painted surface that puts in contact to the work of the artist at a brushstroke-scale. To permit the use of huge imagery for users visualization purposes, we used a virtual texturing technique, a combination of classical MIP-mapping and virtual memory usage [140]. The approach consists in storing tiled images composing a multi-resolution pyramid, and loads only the tiles needed to perform the texture at user request. For each level of zoom, the set of tiles corresponding to the observed texture lookups (2D+level- of-detail/scale coordinates) is determined [141]. The implementation was performed by Zoomify[2], a specific tool that makes high-quality images zoom-and-pan for fast, interactive viewing with HTML, JPEGs, and JavaScript. Also multi touch gestures were developed for a more intuitive interaction with the image.

The mobile application (see Figure 3.3) has been developed for tablet running both Android and iOS operative systems. The whole project was implemented using Titanium Appcelerator SDK[3],a powerful tool to build native cross-platform mobile application using JavaScript and the Titanium API, which abstracts the native APIs of the mobile platforms. Also a useful toolbar was designed to drive the user toward a dynamic fruition of the painting, enabling for a entertaining interaction. The four sections are:

- High resolution:
  the HR image visualization has been incorporated into the mobile application. In this case, to support the user in discovering conceived details of the paintings, a scrollbar with hotspot was designed at the bottom of the screen. This section tells some highlights through magnifications in some portion of the paining. In the meanwhile textual contents facilitate the comprehension, HR visualization is a handy instrument.

- 360 virtual tour:
  exploits spherical photogrammetric acquisition to virtually discover the rooms and navigate the entire museum collection. This function fulfils two aspects: a remote navigation through museum spaces and an improvement in terms of way finding when the user is in the Museum context.

- Sharing: a social network sharing was designed. The possibility to share the art collection and the user experience into the main social network is a best practice in the field of CH promotion.

- Augmented Reality: the device recognizes the tracked image and using this image it connects to internet getting associated images, visuals and 3D shapes, then putting them into the view.

[2]website:http://www.zoomify.com
[3]http://www.appcelerator.com

Figure 3.3: Città Ideale app. The top images show two screenshots of the mobile application, the home page and the High Resolution sections. The bottom images show visitors using the app in front of the painting

For the development, we used Vuforia Framework [4] and, to achieve the best user experience, we adopted image-based tracking system (i.e. markerless), using as tracking images ("trackables") small portions of the painting. In this way the user experience is natural and the continuum between real and virtual is achieved. To drive the user in a more intuitive manner of this tool, an audio-guide suggests the position of the POIs. Once the video stream of the built in camera is on, the device implements a matching with the pre-loaded "trackables", searching for the *keypoints* associated to the images. Then the digital contents are projected on the screen from the perspective of the camera's view, based on the orientation of the device (Figure 3.4). On the portrait we defined 6 different POIs for AR detection and user content overlapping. In particular we tested image-based contents, videos (with transparent background), shapes with text and interactive buttons to cope with social network activities and share contents from the AR application. The virtual exhibitions, displayed in the end-user interface, are dynamically generated based on parameterized visualization templates and database contents. Highlights have been accurately selected by art curators and then stored on a external cloud-based database,

[4] http://www.vuforia.com

that gives the possibility to change or update contents without the necessity to replace the app in the web stores.

Figure 3.4: Augmented Reality application. Contents like images or videos are superimposed over the tablet screen.

3.1.1.3 Results

A first result of this work is the successful creation and the validation of an easy work flow for HD images. The use of the "Città Ideale AR" macrophotography in mobile and web-based applications has shown good performances of the image, obtained in our process. "Città Ideale AR" app, starting from the aforementioned work, proposes an innovative solution of experiencing paintings, allowing to interact with all the available multimedia contents realized for this project. Some key aspects of the application are:

- augmented view of the artwork;
- improvement of knowledge and curiosity about the painting;
- stable POI selection for different lighting conditions.

Besides, we also performed a user test. In order to know the characteristics of the interviewed sample preliminary questions relating to age, academic qualifications, work, and the use of technology in general were initially asked. The system was tested on 15 different human subjects with age between 22 and 48, with different academic qualification and expertise. The question where oriented to understand the relation between the technological skills of the panellists and their knowledge about AR, in relation with the usability of the application (see [50]). Notwithstanding, our purpose was also to make the improvements based on a more rigorous approach, understanding in automatic way the behaviour of the users looking at the paintings. For this reason, the further step was to test eye-tracking technology and collect visitors data, as described in the following scenario.

3.1.1.4 Scenario 2: Understanding user behaviour to enhance AR application development

Developing AR applications for paintings means, first of all, identifying those details that are not visible or conceived in the work of art. Generally, the contents to be shown are decided by art experts that drive the developers towards the highlights, details and curiosity of an artwork. But there are still open questions that we attempted to address: i) which is the best criteria for the selection of contents ? ii) can we identify the user characteristics to personalize contents according to his/her background ? and iii) is it possible to analyse the most observed areas of the painting, to define attention points for AR applications ? For this purpose, we performed a test with eye-tracking for a better understanding of a work of art. In fact, design and implementation of digital experiences cannot be separated from the core component of the system: humans. This is true for almost every domain, even more when we talk about museums. The comprehension of visitor behaviour during their visit can provide needful data for improving the museum exhibition [142]. This might positively affect visitor experience, hence museum's appeal. In a visual approach, like the one conducted to discover details in AR, it was necessary to define a criteria for the selection of focal points for AR applications and for a better understanding of humans' behaviour. This is to provide useful information, analysing the movement of the eyes, in order to define the baseline towards a total User Centered Design for AR applications, forecasting the display of art contents, based on masterpiece features, technological constrains and user typology. The preliminary results showed that the proposed methodology for the definition of AR contents, displayed as POIs in artwork applications, is promising. The choice of using this approach is because the literature provide some interesting studies, even if in relation to art the contribution of eye-tracking is quite recent. For example, in [143] the authors describe statistical regularities in artwork that appear related to low-level processing strategies in human vision, especially for the processing of natural scenes and the variations in these statistics. In [144] the pattern of fixations of subjects looking at figurative and abstract paintings from different artists and at modified versions is described and several aspects of these art pieces were changed with digital manipulations. The authors found that people look at art depending on the subjects' interests and their artistic appreciation. Another paper in which are used eye-tracking technique is [145] with the aim to investigate the influence of bottom-up and top-down processes on visual behaviour of subjects, while they observe representational paintings.

The analysis of the exploratory pattern of viewer and selection of salient visual aspects can optimize AR application.

3.1.1.5 System architecture

Forty Italian students and employees at Università Politecnica delle Marche took part in the study. All participants were young adults between the ages of 18 and 56 ($meanage = 27.9$ $S.D. = 7.8$), equally distributed across gender and had normal vision. An additional group of 12 students was recruited for the pre-testing. The survey included two steps. During the first step, the visual behaviour of subjects using eye-tracking was analysed, in the second step respondents were asked to complete a questionnaire regarding interest and attitudes towards art. A Tobii Eye-Tracker X2-60 and the Imotions®Attention Tool software (vers. 5.7) were used to record the eye-tracking data. All measurements were performed in a quiet room and under standard illumination conditions. Each participant was seated 60 cm from the eye-tracker and monitor. Participants were informed that their eye-movements were recorded. The eye-movement indicators, on which the analysis is based, are fixations and saccades. Fixations are eye pauses over a particular of interest averaging about 300 ms. Saccades are rapid eye-movements between fixations. Each trial started with a 9-point calibration pattern. After calibration of the eye-tracker, the study started with an experimental task (Task 1). The first slide included instructions for Task 1 and participants were free to read and proceed to the next slide. Three famous paintings, all preserved at the National Gallery of Marche (Urbino, Marche Region, Italy), were shown in a randomised order: "The Ideal City" (Unknown author, 1480-1490), the "Portrait of a Gentlewoman" (Raffaello, 1507) and the "Flagellation" (Piero della Francesca, 1463-1464).

During the exposure, the proportions of each painting were preserved. Participants were asked to look freely at the pictures presented. Since previous literature results on view durations varied a lot, the exposure time of the stimuli was determined during a pre-test. Twelve students, with no particular knowledge of art, were asked to observe a faithful reproduction of the picture "The Ideal City" as if they were at the museum. For this test we used the Eye-Glasses mobile eye-tracker. The average time of observation registered was 64 seconds. Based on pre-test results, each painting was shown to the participants to the main study for maximum 1 minute. After the three pictures sequence, respondents were asked to look again at "The Ideal City" picture (Task 2), with six details of the painting bounded in red, as visible in Figure 3.5.

The six-framed details were defined according to the existing AR application for this painting. They include some architectural details that experts considered relevant in this painting: the doves, the vanishing point; the capitals; the landscape in the background; the floor and the geometry that characterize the whole painting.

An on-line survey followed the previous tasks. Participants were asked to focus again on "The Ideal City" painting and to rank the six particulars from

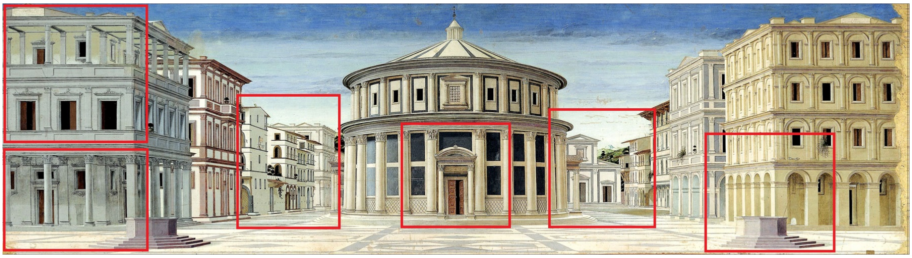


Figure 3.5: "The Ideal City" painting (Task 2)

the most interesting to the least interesting. Then, a set of twenty items was selected to measure participants' interest in art. Subjects were asked to express their level of agreement with a 5 Point Likert scale (from "Strongly Disagree" (5) to "Strongly Agree"(1)). This interest-in-art scale included items adapted from three existent scales (by [146], [147]). Six questions were added to assess participants art experience. Socio-demographic questions (gender, age, level of instruction) concluded the survey. The complete summary of the survey can be found in [148].

3.1.1.6 Results

Data collected were extracted using the IMotions®Attention Tool software and analysed using STATA vers.13. IMotions®provides different metrics for each Area Of Interest (AOI): the Time of First Fixation (*TTFF-F*) and the *Time spent-F*. The *TTFF-F* represents the time to first fixation or in other words, it identifies which areas of interest the participants at first sight saw; while the Time spent-F provides the time spent in a specific AOI. In general, a short time value of *TTFF-F* indicates that the participant's fixation for that particular AOI started immediately as the image appeared on the screen; while a high time value of *TTFF-F* shows that the fixation achieved late or not started. The *TTFF-F* value is equal to the entire exposure time of the image when the fixation not started.

Figure 3.6 shows the heat map, for all 40 participants, when they were asked to observe the painting as they were at the museum, according to Task 1. In this figure, the red colour in the central part of the painting shows that this is the most attracting area. Participants' eyes formed a "vertical line" in the middle of the painting where is the Baptistery is located. This vertical line equally divides the painting into two parts. The heat map shows that, in the central area the number of fixations, during the "free-screening", was larger (1398 fixations) than in the rest of the painting (Figure 3.6). The *TTFF-F* in this area is 0.5 sec, meaning that, as the picture appeared on the screen, participants looked in the middle at first and persistently look in it for quite a long time. The Time spent-F was higher (11.00 sec), as compared to other areas. The heat map, when looking at the *TTFF-F* values, also indicate that once participants have looked in the central part of the painting, they move their attention to the nearest areas. The subjects‘ saccade pattern is defined in Figure 3.6 by the sequence of the numbers from 1 to 7. The number of fixations and the Time spent-F decreases from the centre to the external areas of the painting. While, the *TTFF-F* increases from the centre to the external sides of the painting. Subjects were initially attracted by zone number 2 ($TTFF\text{-}F = 6.5\,sec$, $Time\ spent\text{-}F = 6.1\,sec$ and 763 fixations) and, then by zone number 3 ($TTFF\text{-}F = 7.7\,sec$, $Time\ spent\text{-}F = 7.2\,sec$ and 846 fixations), both very close to the dominant area. The more external areas, including the zones 4, 5, 6 and 7, are characterized by a small number of fixations (zone 4: 63 fixations, zone 5: 92 fixations, zone 6: 44 fixations, zone 7: 53 fixations). In order to deepen the investigation, we relate the analysis of AOIs during the free screening (Task 1) with the results of Task 2, when we asked to observe the painting with the 6-framed details of the AR application. Results show that AOI number 2 collected the highest number of fixations for both tasks. In this AOI, participants also spent the majority of time. The number of fixations for AOI 2 is significantly higher respect to AOIs number 4, 5 and 6 ($p < 0.001$). Results for all the other AOIs, for the two tasks, differed. During the free screening phase (Task 1) participants essentially focussed their attention on the central areas of the

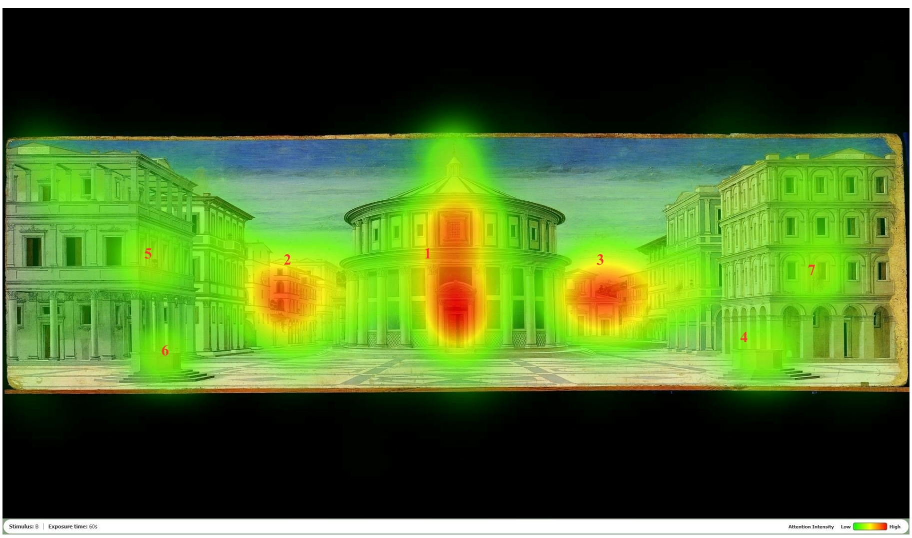


Figure 3.6: Heat map of "The Ideal City" with free-screening

painting, where they spent most of the time. During Task 2, when obliged to follow the instructions and to look at the six red rectangular (Figure 3.7), participants show a higher number of fixations but more balanced among the AOI.

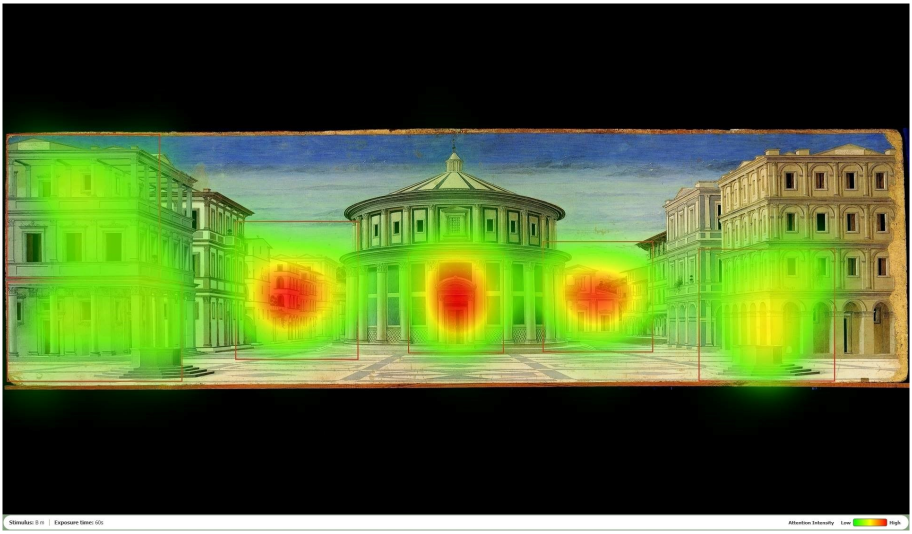


Figure 3.7: Heat map of "The Ideal City" with 6 areas of interest

Results indicate that the attention of participants was higher during Task 2. Both the number of fixations and the time spent increased for each AOI. The number of fixations is significantly higher for all AOI (AOI 1 $p < 0.05$, AOI 2, AOI 3, AOI 4, AOI 5 and AOI 6 $p < 0.001$). Participants spent more time inside each AOI: the increase of time spent is significantly higher for AOI 2 ($p < 0.05$), AOI 4, AOI 5 and AOI 6 ($p < 0.001$). Participants‘ visual route changed when they were asked to follow the instructions (Task 2). In other words, during the free vision of the painting (Task 1) the heat map shows a wider and opened discover of the painting, later, when the view includes the 6 framed details (Task 2), participants only explored the six framed zone. Comparing the two heat maps, the vertical line in the central part of the free-vision disappears during Task 2 and the time spent on the painting is more distributed across the six-framed particulars. The presence of a vertical line means that, according to the respondents, there are other attractive areas that should be included in the AR application. Two areas of interest generated a high number of fixations: the window above the central door of the Baptistery (337 fixations) and the cross of the Baptistery (136 fixations). It is important to note that the area around the cross of the Baptistery, although it was not immediately watched (TTFF-F = 28.8 secs), especially attracted the attention of participants eyes (since the number of fixations was relatively high). The temporal order of AOI (TTFF) also differed in the two tasks. On the other hand, the marginal zones are less interesting for respondents who essentially focussed on the details in the central vertical line and those on areas closed to that. This analysis reduces the areas of interest to 5 zones, all around the Baptistery: the central door, the window and the cross all on the Baptistery, plus AOI 2 and AOI 3 (see Figure 3.6 for AOI codes). Thanks to the information obtained by the users, it was possible to realize a strong and meaningful update of the AR application, that is actually available on the stores [5], [6].

3.1.1.7 Scenario 3: Augmenting 3D models through AR for architectural purposes

The great development of digital mediation in CH domain requires high-quality contents, their usability and visual appreciation by users. Due to advances in computer sciences and availability of digital technologies, in recent years we witnessed to significant changes in architectural representation and survey field. Related to the massive diffusion of both ICT and multimedia mobile applications, a major task in CH valorisation becomes scalability and reusability of multifaceted issues. In representation, analysis and knowledge-based application for Architectural Heritage (AH), as well as for artefacts or paintings, a key content is doubtless the 3D model. Several tools allow creating effective models for representation, visualization, exploitation, dissemination, conservation and restoration. For this purpose can be used 3D models arising from accurate acquisition processes or reconstructions strictly coherent with historical sources. In the knowledge-oriented use of 3D objects, as well as for their management, it is also mandatory that the models shall be fully-featured and semantically or hierarchically divided, portable in various environments, low-cost and derived from many experts. These are hard tasks, because they involve technical and intangible issues: a complete literature is available and today can address considerable advances in the measurement, representation, analysis, interpretation and diffusion of CH. Cultural heritage sites and artifacts get a significant added value from high-resolution 3D models. These models are increasingly available due to evolutions in technology and higher integration of close range techniques such as laser scanning and photogrammetry. Some authors developed in the past years a robust background in laser scanning acquisition and architectural analysis. 3D digital virtual models of ancient heritage monuments come up from on-site data; many works are today focusing on three-dimensional data acquisition techniques and their metric control [149] or on applying VR techniques to simulate and storytelling about architectural monuments, starting

[5] goo.gl/rP3bg8
[6] https://itunes.apple.com/us/app/ducale/id1128703560?mt=8

from existing data [150]. Also archaeological studies are increasingly moving on recording objects by various 3D technologies. These assumptions prelude to a set of case studies, showed below, developed to exploit 3D contents in different scenario and with different Levels of Detail (LOD) and with representation scales from GIS to 3D Cognitive-Information System through a semantic modeling. The study cases presented are the Ridolfi's app and the Bramante's I-Book.

3.1.1.8 System architecture

This section shows opportunities and technical choices in the design of different applications of AR and stand-alone visualization. In the strategy of digital application shown in the following, we applied a use of images that always requires a specific and implicit theory of the image, because the representation is always an act, it is a complete symbolic and discursive practice, impossible out of some form of instituted and shared value's expression trough the image.

For example in the Ridolfi's app we have chooses to show the model starting from the historical drawings of plan. Thanks to the positioning of AR access point at the level of 1.20 metres, this choice enable to visualize the 3D models directly by an axonometric view. The view of the 3D models were based and anchored to the plan, in this way the user can perceive how he has to move around the building for obtaining the right view, i.e. from the square or from the other sides of the building. In the same way, the users are invited to place the tablet in parallel to a façade of the building or covering, to obtain orthogonal projections or prospects and a roof plan. The development of this application allowed to make visible and understandable, but also communicable, the projective reasons for which an axonometric or an orthogonal projection born. The validity of the output has been verified with many school groups (high school and university too) that demonstrated interest and intuition of the projective problem. In other words the use of these applications is very efficient for educational goals.

Conversely, in the case of the Bramente's I-Book app, the models arise from a field survey, which mainly presents segmentation issues. In particular, in the chain of data processing that expects reverse modelling of TLS point cloud or dense stereo matching points cloud; important steps are the cleaning of point cloud, its segmentation and decimation. In some cases, operations of retopology are necessary, but make the problem very complex and difficult to generalize. All these steps enable to find the balance among weight, computational problems and visual appearance. It could be useful to give a classification of the proposed case studies regarding model sources in the following paragraphs: the Loreto's Holy House evidences represent an exploitation and dissemination workflow starting from reality-based models. On the other side, the Mario Ridolfi's app is based on a virtual reconstruction in CAD environment, starting from historical sources. Input models used for the applications are completely different; in fact, while the first applications are made up of models generated starting from points cloud, in the last cases we used polygonal design approach. The implications of this are twofold, including aspects regarding the modelling and texturing process. When a 3D object is generated with Computer Aid Design (CAD) software, it is important to have clean geometries, without line overlapping and vertex explosions. The mapping process is conducted by texturing each geometry individually, leading to uneasy export. Furthermore, models built up in CAD environments generate different workflows and show dissimilar problems, arising from the intrinsic features of architecture.

To reach a high-level usage of mobile AR, limits and challenges still exist and represent difficult benchmark for the scientific community in this fields; of course, such restrictions prevent AR's uptake also in CH domain. All the proposed applications, deal with the balance weight of data quality and its portability in mobile environments or usability by non-expert users. This is a particular task for architecture and archaeology in 3D reality-based models use, but concerns other CH field, as HD images about paintings. Interesting revenue from the research, here proposed, is the definition of a complete framework for generating, managing and visualizing a virtual cultural object. The following case studies contribute to build up and validate the pipeline for a meaningful historical representation using digital objects, as showed in Figure 3.8. The pipeline starts with the data acquisition from different sources and is followed by their process for their optimization and organization; then, the process of simplification is aimed at making them suitable to be exploited, in different platforms, as virtual multimedia objects.

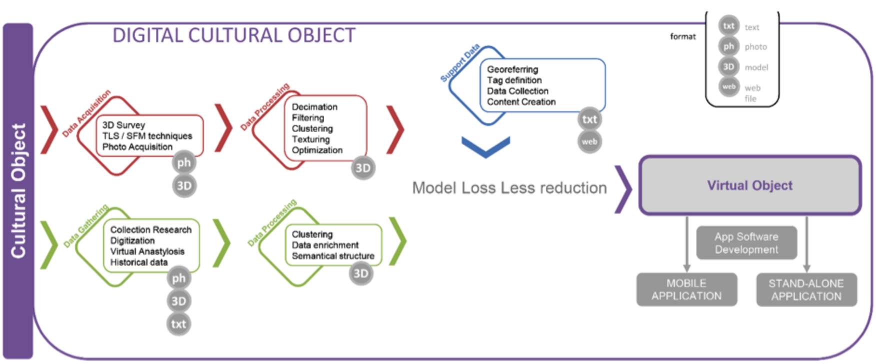


Figure 3.8: Pipeline of digital object development, management and its exploitation in multimedia applications

Each case study presents a set of problems and specific solutions suitable to its main goal and uses all steps to build up the digital object and perform it in the visualization application. Finally, it is worthwhile to mention the specific problem of the LOD management, for which a specific study have been carried out in order to define the best output in relation to the expected result and the input data [74].

3.1.1.9 Results

3.1.1.9.1 Loreto's Holy house app On the occasion of the Fifth-centennial of Donato Bramante's death, the Pontifical Delegation of Loreto allows to survey the Loreto's Holy House: for its marble upholstering some scholars accept the Bramante's attribution. The marble high and bas-reliefs of the Holy House are very complex and fine decorated: they required high quality acquisition with centimetre accuracy, considering the expected visualization output. The survey campaign of the shrine was conducted, during one night, using TLS acquisition and photographic one, allowing to cover the Basilica‘s transept and the Holy House. From the acquisition phase we obtained 38 stand points and a point cloud of 670 millions of points and 618 photos for the SfM survey. The best results in acquisition of marble upholstering were from the photographic and digital photogrammetric survey: we carried out an outside model of 70 mln points. A planned output for this acquisition was an app for tablet, allowing to visualize the obtained 3D model: we performed two LOD for the model. For the whole model a medium LOD: 250k vertices, 500k polygons with png texture 4096x4096 pix. For each box a high LOD: 130 k vertices, 250 k polygons with a png texture 8192x8192 pix. The major challenge was to obtain a good visual appearance of the models, despite the need to contain the polygons number and the textures size. For the development, we used Vuforia (see Chapter 2 for details). The various models were related to images in a book, regarding the history of the Holy House: the associated tag for the complete model was a plan; in this way the user looks at the 3D in an axonometric view coherent with the plan (Figure 3.9). The 3D models marble frames are associated to other historical drawings of the exterior of the shrine. The project was titled "The Bramante I-Book" because adds reality based 3D contents to a physical book, enriching the user interactive experience.

3.1.1.9.2 Mario Ridolfi's APP The Ridolfi's app gives priority to the visualization of the 3D reconstructions of architectural heritage based on resources from historical archives, focusing on Mario Ridolfi drawings. With this app, developed for a temporary exhibition, we pursue the aim to show three-dimensional reconstruction of author's project idea in an involving and engaging manner. The main goal was to communicate to the wide public the

Figure 3.9: The Bramante I-Book: the application shows 3D reconstructions when the user point the related pictures and plans

architecture of Mediterranean Rationalism, a topic not enough known and not simple. The first phase, involving the construction of the 3D digital models, was the core of the application development. We focused in particular on the accuracy and quality of the geometric data, as well as form and measurements; we wanted to create the most reliable hypothetical "reconstructed" design, i.e., the author's "intentions". The procedure to construct the models of buildings followed a workflow which can be summarized as follows: identification of the iconographic documentation, critical analysis and selection of the compositions, conversion into raster format, 2D vectorial redesign with CAD software, and construction of the mathematical models. For the 2D design and 3D reconstructions, the documents were made coherent from the metric and especially the geometrical points of view, retracing the compositional structural generating geometries. Then, to integrate the gaps, we proceeded by critical comparison , making particular reference to Ridolfi's works in the same years (Technical Institute Bordoni at Pavia, Postal Palace in Rome etc.). After the modelling phase, the material enrichment phase was carried out. The models need to integrate available data with regard to the treatment of the model's surface to the façade materials. We analysed the graphics used by Mario Ridolfi in some of his drawings of designs built during the Thirtie's. Then, by analysing the buildings we had already used as reference to elaborate the volumetric model, we obtained the materials he normally used (travertine, Roman peperino, plaster, brick) or those we believed fit best with the appearance of the historical drawings. Following similar works available in the literature [151], the final output in this case needs remarkable operations related to the lossless simplification of the models. The application, consisting of an AR access point and an HTML overlay with static information, presents many similarities with the previous one. For the development, in fact, the same procedure has been used, as well as the same SDK. The main differences lies in the exporting process of the digital contents. The exhibition was made up of a box with three maps of different buildings project and each image presented feature to recall and visualize the corresponding 3D model (Figure 3.10). The main problem in developing the applications was to guarantee the portability of 3D models.

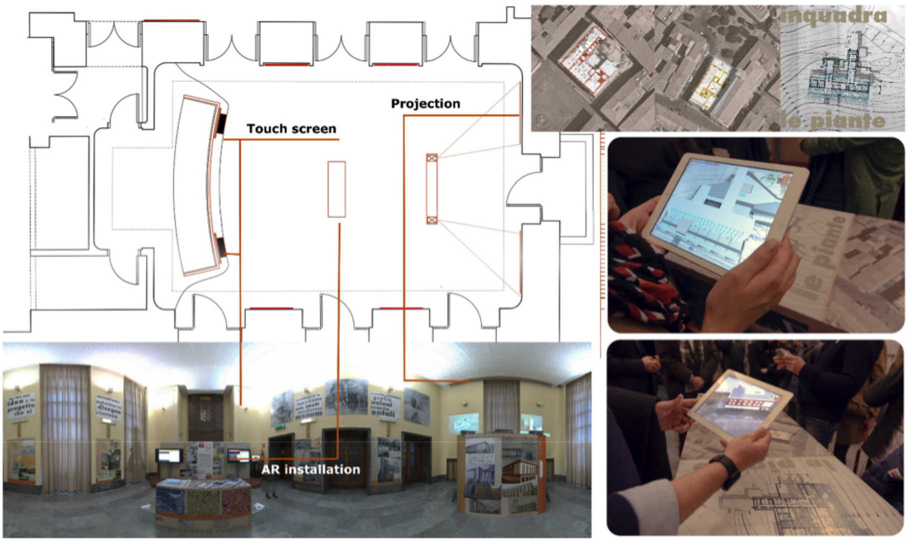


Figure 3.10: The “3D/Thirties architecture” exhibition and Ridolfi’s app

3.1.2 AR and geomatics to support Archaeology

Archaeology underlies complexity and limitations that make the use of new media (and technologies) unavoidable. Two kinds of users can take advantage from this approach: the first ones being the insiders, like archaeologists, experts and conservators. They have access to innovative acquisition techniques allowing a quick and low cost data gathering. The second ones are the visitors, who can exploit the potentials of new ways of communication to improve their knowledge. However, particularly in this field, emergencies, on site conditions and economic limitations makes the exploitation of the media communication particularly difficult. In Chapter 2, we have seen how the particular use of AR technology can give a strong contribution. Because of its nature, in fact, AR allows to make *visible the invisible* [79]. It can be used in both indoor and outdoor scenario, allowing the development of experiences that overcomes the multiple problems we have to face with archaeological settings that are: vastness, emergencies, dimensions, and more. For example, findings are completely freed from the earth which had been covering for centuries but in most cases they must be covered again in order to protect them. AR allows to discover, in an alternative way, monuments or ruins by simply scanning the surrounding environment, loading contents from a remote repository and visualizing them as virtual objects. There would be many advantages using AR solutions for both visitors and scientists. From one hand, additional information can be given at any point of the tour, visitor interests can be closely matched, user interaction supports and increase learning process, Edutaiment (Educational Enterteinment) fascinates children as well as adults. From the other side, scientist and insiders can raise their awareness of CH, have a useful tool to better conducting their research, verify their archaeological interpretation of findings, improve their documentation activity. In this case, also an archaeological site, or the museum of the site, can become a *Senseable Space* with the enrichment provided by multimedia tools. Nonetheless, as discussed before, with the input data, their computation and management is the core component of the system. And more, 3D digital acquisition techniques represent the most popular means for the documentation and digitization of archaeological heritage. That said, in the following we provide an overview of the developed systems to support archaeological settings to be more appealing, informative, and *Senseable*. The proposed scenarios have been experienced within the framework of two research projects; the first one within MIPE (Italian mission in Peru) project in cooperation with CNR-ITABC from Rome that is part of a broader project named PECACH (Proyecto Especial Complejo Arqueologico Chan Chan), for the safeguard, documentation and digitization of the UNESCO archaeological site of Chan Chan, Peru. The second, a national project named Archeofano project, mainly aimed at improving collection, organization and management of a GIS data structure for the designing of the urban-archaeological Roman centre of Fano town.

3.1.2.1 Scenario 1: The virtualization of ancient buildings

In the last few years an important turning point in the way surveys are carried out has been reached. Only a few decades ago, the documentation of archaeological sites was recorded with cumbersome equipment, often expensive and even that produced very little data to be post processed. In addition to this, several campaigns were necessary [152]. Presently surveyors, researchers and archaeologist are finally exploiting a broader set of convenient tools (i.e. range-based, image-based, sensor-based systems), which allow the gathering of a great number of low cost information in short time. The worldwide diffusion of close range photogrammetry applications has enormously increased the adoption of reality-based modelling as the primary technique for the documentation of CH. Several research works demonstrate how reality-based 3D survey is probably the best source of knowledge for any work of documentation, cataloguing and preservation. It is suitable for large archaeological sites, to represent their artefacts as well as small and medium size findings. Advantages of this method are twofold: on one hand, it represents a strong simplification for insiders [153]; as a matter of fact, the visualization of any type of digital model regarding archaeological artefacts, can be a support to activities like investigation, interpretation and development of a hypothesis. On the other, the virtual reconstruction of ancient findings represents the backbone of CH dissemination through different digital platforms and means. In spite of the variety of available techniques, in the archaeology domain a sole documentation pipeline cannot be defined a priori, because of the diversity of archaeological settings. For architectural complexes, for example, a survey has to follow specific rules in order to achieve the best results in terms of both completeness and accuracy [154]. Furthermore, in the case of perishable material such as mud brick buildings, there is a real need to proceed with fast and agile tools as well as to face unplanned acquisition campaigns.

In this scenario the proposed approach provides a complete pipeline of survey for the safeguarding, documentation and the fruition of archaeological remains. In particular, the proposed workflow is based on the combination of different technologies. Specifically, we have firstly built the overall frame of an historical building by spherical photogrammetry; hence we completed the survey by using dense reconstruction techniques. The main contribution of the aforementioned approach lies in the integration between Multi-Image Spherical Photogrammetry (MISP) and Structure from Motion - Multi-View Stereo (SfM-MVS) workflow. MISP is a photogrammetric technique based on spherical panoramas, which is the cartographic representation of the sphere where the projected images are taken at the same point [155]. SfM-MVS techniques have been adopted because they are needful to augment virtual reconstructions with high photorealistic contents. Some geometrical constrains and the precarious conditions in which we operated, made impossible the reconstruction of some parts; to overcome this issue, a close cooperation between 3D modellers and archaeologists (together with ancient drawings and documents) led to a progressive refinement of the reconstructive hypotheses, documented in the paper. The aforementioned approach was tested on Chan Chan which is probably the largest pre-columbian archaeological site built in adobe, visible in Figure 3.11, that shows the Huaca Arco Iris in its actual conditions.

The detailed description of the method was published and can be found in [85]. The outputs of this specific case, as well as other acquisitions conducted by the authors, have been processed and exploited in a real case exhibition at

Figure 3.11: Large coverings that spoil the visual impact of the building and decorations.

the museum of the site, in order to make them visible to the majority of the visitors. In fact, Chan Chan vastness and its impervious conditions make the visit limited to a little amount of findings. The architecture proposed in the following attempt to overcame all the aforementioned issues.

3.1.2.2 System architecture

The importance of the whole set of data gathered is twofold: first of all a complete metrical reconstruction of the site provides conservators with a fundamental starting point for restoration works. Secondly, these data give the possibility to create a virtual corner for their exposition, moving from the scheme of a classical exposition of findings towards a digital and interactive visualization. The scheme reported in Figure 3.12 shows the complete pipeline of work that includes data acquisition of many complexes of the site, data processing and content creation for the exhibition. This last, installed into the Chan Chan museum, is composed of three main installations. The first one is an AR application that was developed to discover the archaeological findings hidden by earth. In [79] a location-based solution was developed to test the performances in outdoor scenario (in this specific case the app was developed to visualize the central entrance door of the main square of Palacio Rivero). However, the site is not opened to the public, hence we propose a marker-less solution of the same artefact, supported by a wall mounted poster displaying a high-resolution image. The final result is the overlapping of the 3D model (gained with Structure from Motion techniques) of the rests in the corresponding position. The second is the visualization of a virtual tour of the site, created with a previous reseach work [156]. The third section consists on the visualization of the 3D model of a temple and the related bas-reliefs, which embellish the structure, through the use of an advanced web-browser.

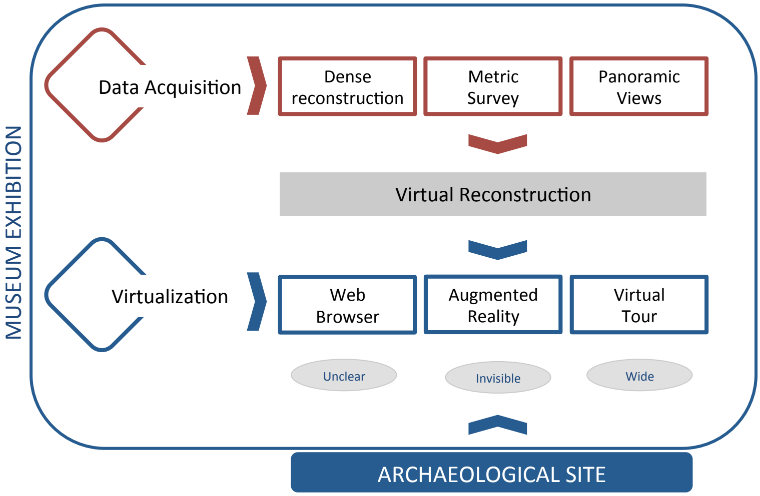


Figure 3.12: Pipeline of digital object development, management and exploitation in multimedia applications. Oval labels represent the problem that each technology is able to solve for a complete fruition of heritage goods.

3.1.2.3 Results

The work conducted for the development of the museum's installation is backed, as referenced in the previous pages, by several research works. However, it in not the purpose of this thesis to describe the details of the single methodologies, rather than to provide an general overview of how the single applications can become part of a wider installation; hence, in this section the results should be intended as the final set-up, which embraces all the computation performed for the digitization of the site. In the following we report some significant outputs from the installation. In the exhibition it is possible to use a web-browser to navigate among the virtual 3D reconstruction of the whole complex and its bas-reliefs.

The final result is reached with a wall-mounted poster containing the 3D model representation of Huaca Arco Iris, with the correct position of the decoration (Figure 3.13). This last was labelled with the same code of the web browser, so that the user can interact between the artwork and the digital tool. The 3D reconstruction displayed in the poster arose form the methodology previously described.

Figure 3.13: The wall-mounted poster representing the 3D virtual reconstruction of Huaca Arco Iris. Decoration has been labelled with E (stand for External) and I (stand for Internal) to help the user orienting during the navigation.

Some pictures of the web browser shows the high accuracy that was reached. The work has been realized through the use of some basic libraries for the 3D Web rendering: WebGL, Three.js and Tween.js. The first is needed for the real time visualization of the scene. In order to be able to display 3D objects in a proper manner with Three.js, a scene, a camera and a renderer are needed, so that the model can be rendered in real time. The scene variable is a container that is used to store and keep track of all the objects that we want to display. The renderer is responsible for calculating how the scene will look like in the browser, based on the camera angle. Finally, Tween.js was used to develop transitions of properties. The first outcome of the Web-Interface of Huaca Arco Iris is summarised in 3.14. The screen layout has a main area, including the Huaca Arco Iris structure with its bas-reliefs in the real position. The visitor is placed in a first personal perspective view. Regarding the usability, particular attention was given to the simplicity of use and to ensure that the user could reach the desired result in an accurate and complete way. With just a few intuitive steps it is possible to explore all the areas of the archaeological site.

Each bas-relief is highlighted on the structure so the attention can be focused on it. A further aid to usability is given by the fact that with simple keyboard operations it is possible to change the camera position and to choose the type of light that illuminates the scene. The bas-reliefs rotation angles were restricted to ensure a proper frontal visualization. Likewise zoom, horizontal and vertical displacement are bound to not give to the user the feeling that the object can leave the scene. The entire scene objects are suspended from the ground for two reasons, the first is to make the user aware of their interactivity and the other is to put more emphasis by releasing them from the rest of the scene. During the switching between structure and bas-relief, the camera position is saved: in this way it can be restored at the end of the bas-reliefs tour.

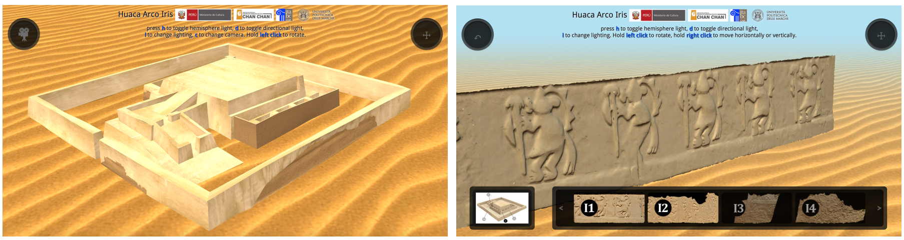
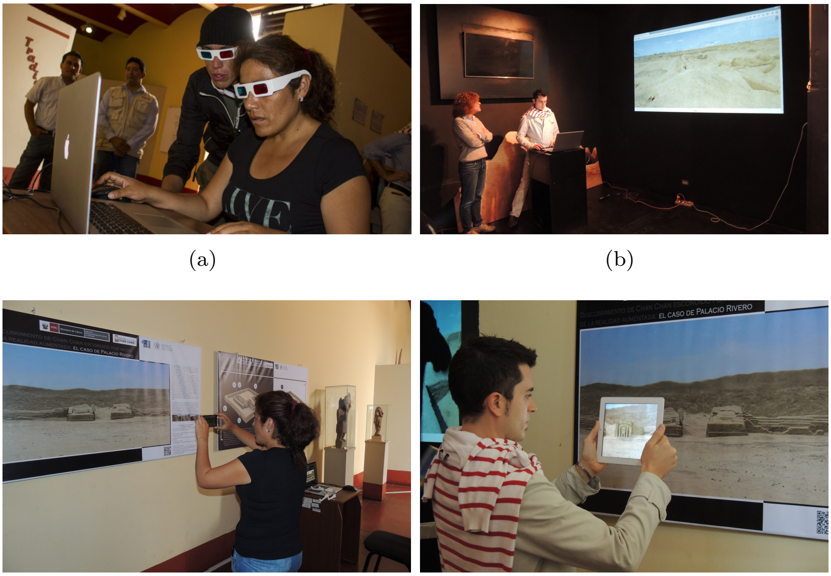


Figure 3.14: a) The structure when the browser is opened. The darker areas are the bas-relieves visible from the current point of view. If the mouse is above the bas-relieve (number 7 in the picture), its area is highlighted and a tip is shown. b) The sidebar is active and the user can choose the highlighted bas-relieve.

The rest of the installation can be seen in the Figure 3.15.

3.1.2.4 Scenario 2: GIS and Augmented Reality

The achievement of good practices and sustainable workflows to manage heterogeneous data for archaeology has been made possible thanks to the exponential growth of digital tools for data registration, acquisition and management, mandatory at each level and essential to preserve and protect cultural heritage. During the last decade, different approaches have been experienced for the digital documentation of excavation, providing interesting solutions on computerization flow especially for GIS [157]. Although the delivered functionalities are gradually improving, a real integration between digital methods in the archaeological pipeline is still broadly missing. Further, it is well known that archaeological activities give in output a huge amount of data that are very difficult to be stored into a complex structure because of their heterogeneities in terms of source information, chronological parameters dissimilarity and findings classification [158]. Therefore, it is paramount to find a "common language" representing the key for integration [159]. Furthermore, there



(a) (b)

(c) (d)

Figure 3.15: Museum installation: a: visitors looking at the web site in anagliph mode. b: the virtual tour of the Chan Chan site. c and d: visitors exploring 3D models in AR

is the necessity to satisfy both internal (cataloguing, documentation, preservation, management of archaeological heritage) and external (communication through the web portal) purposes, a good interpretation suggested in [160]. The approach described in this scenario faces these issues and tries to outline a method to avoid the drawbacks arising from the aforementioned inconsistency. The experience was carried out within the ArcheoFano project [161], mainly aimed at improving collection, organization and management of a GIS data structure for the designing of the urban-archaeological Roman centre of Fano town, in Italy.

3.1.2.5 System architecture

The objective is the visualization of a 3D model in-situ, tracking the real environment and providing the user with contextual-awareness services; we focus over an interesting workflow, to manage heterogeneous data for archaeology, made up of the following steps: data collection, generation of a conceptual model for data management, data organization into open source GIS environment, visualization of 3D data (see Figure 3.16).

The whole complex of structured data has been stored inside an open source

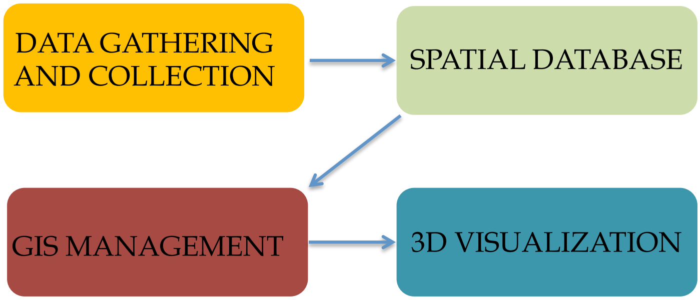


Figure 3.16: The workflow to create an AR visualization experience starts from the data collection, their storage and management until their visualization. Every step is mandatory, since the metadata and attributes are necessary to move on the following step.

GIS environment, which in turn is related to a GEO-DataBase. Considering a Roman Theatre as a POI, it is possible to create a table containing all the useful information such as latitude and longitude (to correctly register geo-location), title, description and other information of interest for the user, experienced through a location-based AR service. In the first step the model implemented in the mobile application was the 3D model obtained from the TLS point cloud of the remains. The point cloud model was decimated and smoothed and the mesh model was exported. In a second step, a virtual reconstruction of a Roman Theatre (Fanum Fortunae) was built with data arising from an urgent partial excavation, while the complete 3D virtual model is an interpretation based on several sources, mostly on the Vitruvius Treatise. The process consists of a digital anastylosis starting from historical and metric sources, which details can be found in [66]. The work of modelling used as base material the 3D TLS acquisition of the excavation. Adapting the Vitruvian scheme to the dimensions detected in site and completing the missing parts with elements taken from contemporary theatrical structures has been able to represent the hypothetical plan of the structure. By exploiting data related to the heights and the indications of "De Architectura", the representation has been completed, taking into account sections and façade. The Roman theatre of Fano was conceived on the base of a well-defined architectural type and placing on the base of the building a generator module that governs the whole building. Since the remains found related to portions extremely small and fragmented of the theatrical structure, special attention was paid to the construction of a model that was generally correct and able to bring together the findings from the various essays. Following the aim of making the model browsable, each of its parts has been completely and correctly represented, independently from the scale of representation and direction of view, so that it could be observed from any point of the space.

3.1.2.6 Results

In the modelling phase particular attention was given to the LOD. The accuracy and the precision used to realize a shape can lead to excellent results in the final processing phase, especially with regard the architectural details but, at the same time, can represent an obstacle if geometry is excessively elaborated compared to the operating power and performances of available supports. The application was build according to the following steps; the 3D model was exported as *.obj*, because of its capability to maintain the original file object and the possibility of being edited. Layar is the framework chosen for this case. This platform make available two key features: the first is a tool (named Layar model converter) to convert the obj file into a format suitable to be managed in AR. The second is the possibility to define a geo-layer, ready for being uploaded to a web-server. In the database we built a table containing, geometrical transformation (6 Degree of Freedom (DOF) and the scale factor), description and link to external resources. More in deep, we stored the POI within the database table linked to the application created specifically to contain them; in particular, about each POI, is essential to store latitude and longitude (to correctly register geo-location), title, description and other information of interest for the user. The parameters to correctly locate the model above the screen are: latitude, longitude and a radius of influence. Within the circle of specified radius, the application seeks for relevant POIs, starting from user's location. Once the user is in the area of interest, the application is able to retrieve context information and to visualize the 3D model in the exact position of the excavation (see Figure 3.17). User location is based on the GPS and inertial sensor built into commercially available device (in our case iPad air) where the accuracy is low. Even if the positioning output is error prone, after several adjustments (in terms of scale and coordinate) we reached a satisfactory result. Figure 3.17 shows the AR visualization of the 3D model in the same location of the Roman findings.

3.2 Senseable Public Open Spaces

Today, 54 per cent of the world's population lives in urban areas, a proportion that is expected to increase to 66 per cent by 2050[7]. The quality of human life thus depends considerably on the quality of the urban environment, and this

[7] http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html

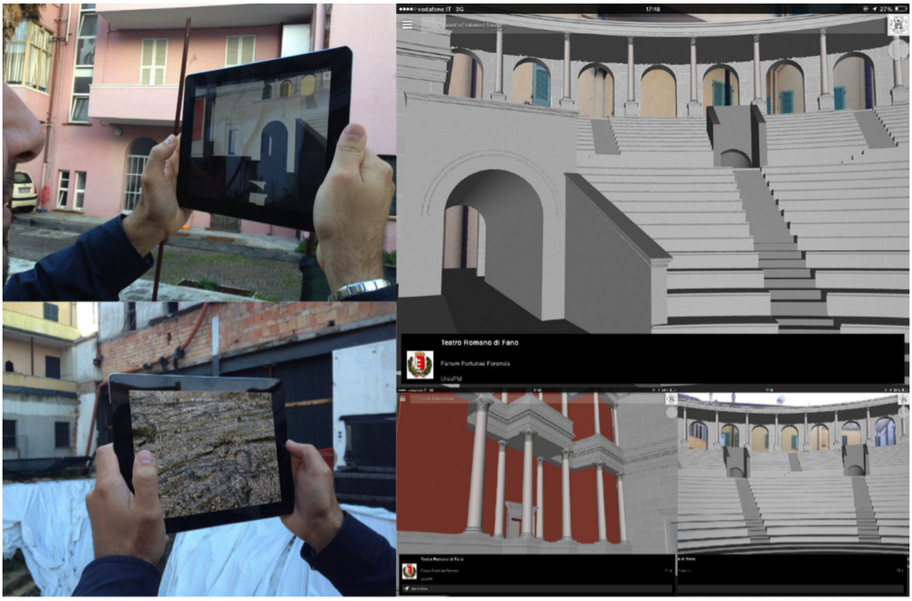


Figure 3.17: AR visualization of the 3D model of the Roman theatre of Fano: all images show the virtual anastylosis model, bottom on the left a screen shot of the reality-based model.

in turn depends on the quality of Public Open Spaces (POS), which should be accessible to all on equal terms. To achieve a socio-spatial equity, the right balance between “built”, “green”, social and other components has to be pondered. This makes the process of production of POS a very complex task. On the other side, ICT and mobile devices, as a key achievement of human being, are profoundly affecting all facets of life. This affects also the way people experience time and space. ICT, besides awakening a strong interest and attraction for many people in their everyday life. Increasingly, we experience people using mobile devices in public spaces. On the other side, ICT enable new tools for supporting urban development, and as equipment for furnishing of public spaces. Both, intertwining the digital and the physical worlds, create that hybrid space we call *Senseable Spaces*. In other words, the mediated space brings a dynamic and hybridised aspect to the physical space [162]. It results as a logical continuum of the progress in our every day life, as ICT helps us in business, at home, is increasing interfering in our leisure activities. Even if there are relevant cases where the adoption of ICT has made the use of POS more “smart” [163], the possible interrelation and the recognition of an added value, are still not very elaborated. It is important to understand the whole range of possibilities offered by ICT; as it goes from analysing of big data, to supporting public involvement processes and to aid their planning and design. In cities, there are less and less natural spaces, so mainly the focus needs to be set on the improvement of existing POS, making them more usable and attractive to more people, while preserving natural and cultural identity. ICT can upgrade a POS to the quality of *Senseable Space*, since their contribution is twofold: on the one hand, they provide users with new instruments to enhance their experience of visiting and discovering a place. On the other, they represent a valuable source of information that could be used for the planning process. It is important to understand that, ICT are not just an "add-on" to a place, but represent a boost for planners during the design process. It is very useful to include ICT from the beginning when analysing the urban territory, in order to help gathering and analysing data. Using ICT provides new possibilities for urban planners and designers, and landscape architects. Monitoring and tracking the so-called User Generated Data (UGD) represent the future pathway for observing, recording, and analysing the dynamics of our environments (i.e. cities, POS, rural areas, etc.) and, more in general, the behaviour of people who live and enjoy these spaces. For that, a big challenge is posed by the use of mobile devices, which are already significantly changing the way people interact with their surroundings. The combination of sensing the environment and user locating plays a pivotal role in the mainstream of data collection.

All the scenario reported in the following, have been experienced within the framework of "Cyberparks - Fostering knowledge about the relationship between Information and Communication Technologies and Public Spaces" is a network of 70 experts from different working fields and scientific domains, coming from 29 different European countries and financed for four years (June 2014 _ May 2018) under the COST Framework[8].

3.2.1 ICT and Public Spaces

Internet, wireless networks, tablets and smart phones, bluetooth and others represent the main communication mediums. Among all possible opportunities opened by ICT, one of the most important for the *Senseable Spaces* concept is the communication aspect. New ICT devices not only enable new forms of interaction, but also strongly attract people to communicate in real-time with others. ICT also enable gather information about places in a bigger scale. The transformation of ICT into an inherent part of society triggers the grown ICT into an important social media. It is turning to be a big part of contemporary life, people more and more build and maintain their social relationships

[8] http://http:www.cost.eu/domains_actions/tud/Actions/TU1306

through various social media, and this affects increasingly the way they organise their everyday lives. For this reason, ICT is often studied in the context of how modern communication technologies affect the interactions between people and society. Relevant for understanding the interaction between ICT and public spaces is the feature of ICT to allow "on demand" access to the contents, any time and from nearly anywhere. Hence, the property to engage individual users as well as groups of people to interact and congregate on-line and share information, and bring them to be outdoors, are relevant aspects. The digital footprints, left by individuals in their daily activities can be used as data for statistics, and extracting metrics about socio-spatial behaviours, directly from the source (public space users). This information are geolocated and embody numerous opportunities, as they offer the possibility of working with high spatial and temporal data, always available and always updated. The advantage of collecting digital footprints [18] ranges among different domains. One field, which can benefit from better ICT-space interaction, is the tourism sector. As it is very much related to the quality of place, on-site information and analysis of visitors' motivations and behaviour.

Several actors have been outlined up to now; however, from the scenarios of this section, two main kinds of users will arise: visitors and planners. Visitors, who can have access to interactive experiences and, even if with little knowledge of a certain area, can naturally experience unfamiliar places. They can be tourists for a short period of time, searching for new and unique experiences. Residents are those who living in the vicinity will use the place in their daily lives if it suits their needs. Researchers are those who look for specific information that a place should contain (e.g. fauna, flora, geographical location or socio-cultural and spatial aspects). Planners, who are claimed at creating spaces that are able to satisfy the users' expectation. The examples reported have a strict connection with tourism (and in particular to that tourism oriented towards heritage sites), in both terms of giving and getting information to the users and from them.

3.2.1.1 Scenario 1: experiencing CyberParks

Location-based Augmented Reality (AR) has successfully grabbed the tourism industry. This is because, among other peculiarities, AR has the capability of changing users' sight of the environment. The growing potentials of mobile devices are definitively changing the way in which tourists gather and access information, especially in outdoor environment [111]. The traditional orientation, guides and way-finding maps, have been overridden by the relentless diffusion of mobile orientation devices and on-line maps, more suitable and accessible to users needs. However, a trivial and common thought, preventing AR from being a world-wide reference in this domain, is that mobile maps are a good solution to find places and interesting areas in outdoor spaces. However, even if well-established solutions, are not optimally designed for urban exploration and provide limited capabilities to access data; moreover, and more important, they oblige the user to look away from the reality. Another issue of currently available 3D maps is that the camera view of the object is often occluded by nearby structures, which is especially problematic in densely built-up areas [110]. AR represents instead a natural choice for exploring location-based information of real world, mainly because information can be superimposed onto the display, with the same sight of the user. Simply by framing his/her surroundings, the user can easily access additional information about a building, in urban environment, by pointing an AR-enabled mobile device into its direction, regardless of the visual barriers. In [112], the authors have listed a set of challenges that developers have to take into account designing AR browsers for outdoor environments; many objects can be augmented with information; each object can be a source of a substantial amount of information; contents might be visually heterogeneous and dynamic; users are into unfamiliar environment; tourists have information needs which differ from those of dwellers. These considerations represent a useful reference also dealing with archaeological heritage [122], defined in the literature as “Cyberarchaeology” [164]. Forte states that Cyberarchaeology aim is to build a spatial-temporary environment able to reconnect the current archaeological landscape with the ancient one, following a validated and transparent methodological path. AR allows to develop the “simulation process” directly on site. In recent years, many AR systems have emerged. However, the vast majority of these systems are intended for small indoor environments, easier to control because of the limits derived by known issues (e.g. brightness variation, occlusion, 3D registration, etc.) [165]. The development of AR applications for outdoor scenario implies the use of built in sensors, handy and spread for the majority of devices, but error-prone in terms of accuracy.

The main objective of this work is the development of an AR experience for cultural communication, designed for mobile devices in outdoor environments. The project aims at enhancing the Cardeto Park (Ancona, Italy), focusing on personal experience to provide tourists and visitors with an interactive tool to discover the hidden secrets of the park. This research underpins two main aspects. The first one, theoretical, is that AR and mobile technologies would represent the milestone for the promotion, the use and the conservation of archaeological parks. We propose a shift, through new technological tools and new contents, with the twofold objective of making the visit experience easier and complete, with a greater involvement of visitors, bridging the gap between existing and accessible, between visible and invisible. The second aim, more technical, is to challenge the development of an application by merging a well established state of art location-based services with an edge-based tracking system. The idea is to use an hybrid approach, integrating into the same application the two aforementioned tracking techniques. Our test demonstrates that the latter is a performing tracking system also in outdoor scenarios, where lighting condition and the variety of landscape hamper an affordable use of marker-less solutions based on image matching. We also outlined best practices suitable to be adopted for further exploitations of open-air cultural heritage.

3.2.1.2 System architecture

This project is concerned with the proposal of a change in the use of the park: new technological tools and new contents communicate with the dual objective of making the visit easier and straightforward, improving the involvement of visitors. Actually, the park presents some weaknesses such as the complete lack of orientation and the inaccessibility for the majority of the buildings. With the introduction of digital service, the expectation is that there will be a change in the use of the park, bridging this way the gap between existing and accessible, between the visible and invisible. The current condition of the trails is of semi-abandonment, with few sporadic way findings along the way (Figure 3.18).

Figure 3.18: One of the main entrance of the park. The lack of care and signs makes the park inaccessible and difficult to visit.

The app, accessible by smartphone or tablet, allows visitor to choose from different visit trails. Accordingly with his position, the tourist can chose among different pathways. By different tracking techniques, further information are made available every time a user gets close to a specific POI. The site's map, with highlighted the main entrance points, is shown in Figure 3.19.

Figure 3.19: Map of the park with all the starting point highlighted in yellow.

For the development of the proposed application, we have chosen to adopt two tracking systems. Location-based tracking and edge-based tracking. The first one is based on the user location and enables the smartphone retrieving context information accordingly. The second one is an *Object-centric* approach categorized as marker-less tracking, based on geometrical edge features [166]. The reason why we have chosen to merge two tracking system into the same application, lies in the possibility to exploit the potentials of both systems. Location-based helps way finding, triggering services only at a specified distance from the POI. Furthermore, in absence of signals, as for this study case, it helps a visitor to follow his preferred path according to the POIs typology. On the contrary, once the tourist is close to the cultural good, the location-based service cannot provide in-depth analysis of cultural objects. The development of Augmented Reality experiences, in fact, is strictly dependent on the type of registration (i.e. overlaying of virtual contents) that one chooses. Delivering in-depth analysis of specific objects, requires robust tracking techniques able to anchor the real object with the one displayed in the camera of the device. With edge-tracking, enabled only at a certain distance from the POI, the user is provided with a more precise registration of digital contents. It is a state of art method used to mark the points of digital image in which the light intensity changes abruptly. Abrupt changes of the properties of an image are usually the symptom of important events or changes in the physical world in which images are the representation. These changes can be for example: discontinuity of depth, the discontinuities of the surfaces, changes in material properties, and variations in ambient lighting from the surrounding environment. In the following subsection, the two methods are discussed.

This functionality has been developed to permit the user activating the augmented reality browser and to search for all the POIs close to him/her.

All the POIs have been stored into a Relational Database Management System (RDBMS), with a classical web-server which hosts php pages. For this experiment we have chosen an open source MySQL server. POIs have been stored within the database by assigning them a table with specific parameters like latitude and longitude (to correctly register geo-location), title, description, link to external resources, metadata and other information of interest for the user. A web-service is needed to collect the POI information (in JSON format) and get it back to the AR platform. These parameters are computed by the application, permitting to overlay the labels into the real scene. To retrieve these points according to user's location it also necessary that the application generate a php script that returns the POIs. Performing a series of asynchronous calls to activate the php script it is possible to transfer the user's location coordinates as parameters. A brief explanation of the architecture can be found in Figure 3.20.

All the features of the app have been implemented by using libraries provided by API LayarSDK. A compass, displayed on the screen, helps the user in orienting among the different POIs. In this way, the user is guided to reach the area where the wanted item (a building or a specific finding) is located. To implement this feature we took advantage from the set of embedded sensors of mobile devices (e.g. compass, gyroscope, accelerometer and GPS receiver). For adjusting the search area, the user can set a search radius from the device. Within this radius, the application looks for relevant POIs. This is particularly helpful during the visit to retrieve information of a limited set of POIs nearby the user. Moreover, the application allows displaying, in a popup window, more information (the title, description, footnote and image) associated with the selected, as well as the cultural good typology.

3.2.1.3 Results

The particular case selected for this work encompasses a various CH, including Romans relics, as well as buildings dated the Second World War. By catego-

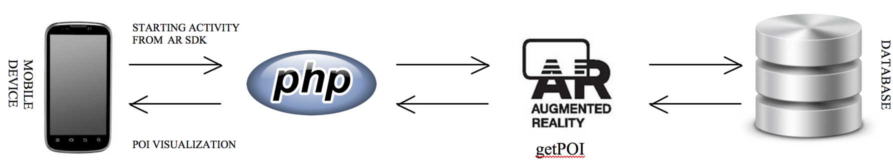


Figure 3.20: The steps of the architecture during on site visit.

rizing all the POIs, we have given the possibility to follow specified trajectories among the park. Some screen shots of the application running are shown Figure 3.21.

Figure 3.21: Mobile application running in the park, in way finding mode

The recognition of contours (edge feature detection) is the second tracking technology used for the presented application. This tracking technique is particularly suitable to augment:

- a previously defined solid 3D object from any view angle on a non-planar environment;
- different objects independently of their texture;
- the scene to obtain the scale of the environment;
- objects in an unpredictable environment where motions and changing lighting conditions make image matching difficult.

To obtain this function, the following steps have been implemented into the application. First of all we have built the 3D model of an historical building within the park and preloaded it into the system as a tracking object. In this case an ancient barrack. Within the app, the edge detection process has been implemented with Canny algorithm [167], running once the device's camera is enabled. An example of the edges extracted from camera frame is showed in Figure 3.22.

The 3D model is managed by the Layar SDK, allowing the matching between the edges of the image from the camera and the edges of the 3D model, managed in wireframe with hidden line mode. Once the user has reached a specified POI, for instance, is closer to it by a given distance (e.g. less than 50 m) and the cultural object is in the line of sight, the navigation switches into

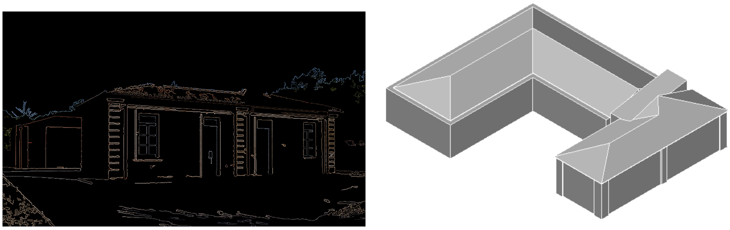


Figure 3.22: Steps for the implementation of the edge extraction from the real scene.

edge-tracking mode allowing the visitor to display more detailed information. The initialization starts with predefined views from several locations in the environment, according to an initial pose, setted up by default, that specifies a rough initial estimation of the camera position and orientation to the target object. In order to avoid visual occlusions, the tracking 3D object has been developed to appear in *Silhouette* mode

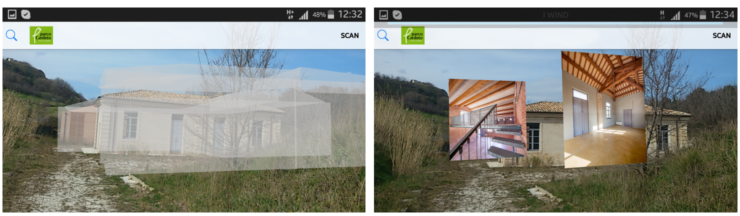


Figure 3.23: Mobile application running with edge tracking enabled near the POI.

In this specific case, since the building access is forbidden to the public, the application allows the visitors to virtually explore the interiors with their related pictures (3.23).

3.2.1.4 Scenario 2: Analysing human movements at mass events

Public events, such as sporting matches, festivals, street parades, concerts and exhibitions attract a great number of visitors. People monitoring systems are able to measure the flow of people entering and leaving a pre-defined area.

Creating an automatic system able to estimate the volume of people in a dynamic environment is a very important task for several applications. Knowing the volume and the movement of people in major public events offers interesting business possibilities for the organizers [168]. For example, automatically knowing the number of visitors at each entrance of very crowded locations, such as a stadium, is highly important for security. Besides, understanding the moving behaviour and identifying the most attractive points help the organizers to reduce costs and risks by a better management of flows.

In literature, there are several works on human behaviour, oriented towards the analysis of collective behaviours in crowded mass events [169]. Very interesting is the work of [170] where the authors use Bluetooth technology to monitor the spatio-temporal dynamics of visitors at a mass event: the Ghent festivities, one of the most famous outdoor cultural events in Europe that attracts million visitors. They also put in evidence the efficiency of Bluetooth technology with respect to other technologies used for monitoring people in crowded environments.

Bluetooth technology is increasingly taking hold because it is simple and low-cost for the analysis of spatial behaviour [171]. Due to its nature, Bluetooth technology has the ability to simultaneously monitor and track a large number of people and for this purpose it is particularly suitable for applications that study human behaviour in crowded areas [172]. Other technologies described in literature to automatically measure flows of people are surveys, video surveillances, GPS and then Bluetooth [168]. Considering survey, the problem is that this solution is expensive and the sample considered is not representative of all visitors, due to their dishomogeneity. In the second method, concerning video surveillance [173], the weather conditions significantly affect the efficiency of measures depending on illumination, lighting, brightness, shadows, in addition to the problem of occlusions that mostly occur in crowded environments [174]. One of the main problems of GPS technology is that it can not be used in many indoor environments due to the lack of GPS signal and also the hardware is quite expensive. GPS is not efficient also in urban canyons, where the calculation of position is not univocally determined and the signal can be unstable and/or absent.

The following work proposes the use of Bluetooth beacons as quantity sensors for investigating complex motion dynamics of visitors at a mass event: the 10^{th} Edition of Mogliano Halloween Festival, which counts every year thousands of visitors in one night. The system architecture consists of several smart beacons located in different festival stands, a mobile application freely provided to visitors, Automatic Vehicle Monitoring (AVM) computers and a remote dashboard for data storage.

The paper aims at highlighting the potential of Bluetooth Low Energy (BLE) technology for understanding such crowd dynamics, and thereby complements the (little) quantitative data that are currently available. For this purpose, preliminary tests have been conducted for demonstrating how in general the proposed methodology could be needful for stakeholders of events and urban planners. Moreover, the main novelty of our proposal is the service offered to visitors providing push notifications giving in real time information concerning stands and recreational areas, extending also the possibilities to plan and affect visitor trajectories with way-finding services. Notifications also concern real-time information on the bus shuttle service with the available parking areas around the "festival area". In fact, the shuttle buses are equipped with AVM systems. AVM provides the real time location of a bus and also counts the number of passengers, with the aim of avoiding overcrowding. Furthermore, using the data storage procedure, it is possible to obtain statistics on visitor counts, the share of returning visitors and visitor flow maps, giving also the possibility to distinguish different patterns.

The final goal of the project is the design of a general framework for event management and simulation, with a strong focus on safety & security, flow management and event flow simulation, digital footprint analysis for learning from past events, etc. This framework is novel in the field and has a strong impact on international mass events.

3.2.1.5 System architecture

Analysing spatio-temporal dynamics of visitor movements in a mass event is a hard task, especially if the scenario is a mixed indoor-outdoor environment, or urban canyons. Planning this kind of events should be entrusted not only to qualitative data; the use of quantitative data permits public authorities and planners to undertake decisions with more awareness. The use of proximity technologies could help in collecting many types of information. For example, the crowdedness of a certain attraction, patterns of visitors among the festival and duration of their visit are useful data for planners. By combining smart technologies on shuttle buses it is possible to know in advance the amount of people arriving at a certain time. Also visitors of a public event could benefit from these technologies. In fact, it is possible to offer them a better transport service thanks to real time information (i.e., timing, position, etc.), improving the fruition of the service.

The proposed system is designed to manage the overall event. The advantage of this kind of monitoring tool is twofold: on the one hand, it provides real time data to dynamically drive group of people towards less crowded attractions, owing to flow estimations. On the other hand, the collection of large scale statistics could be used for future planning of the same event, to enhance the arrangement, the accesses and the security services. The main components tested of the architecture built up for this scenario (beacons, mobile devices and AVM digital footprints), are shown in Figure 3.24, but this architecture is open to future integration of different sources of digital footprints. Event visitors have many ways of leaving voluntary or unintentionally electronic trails: prior to their visit, tourists generate server log entries when they consult digital maps or travel web sites; during their visit, they leave traces on wireless networks whenever they use their mobile phones; after their visit, they might add online reviews and photos. Broadly speaking, there are two types of footprints: passive and active, as largely discussed in Section 1.2.

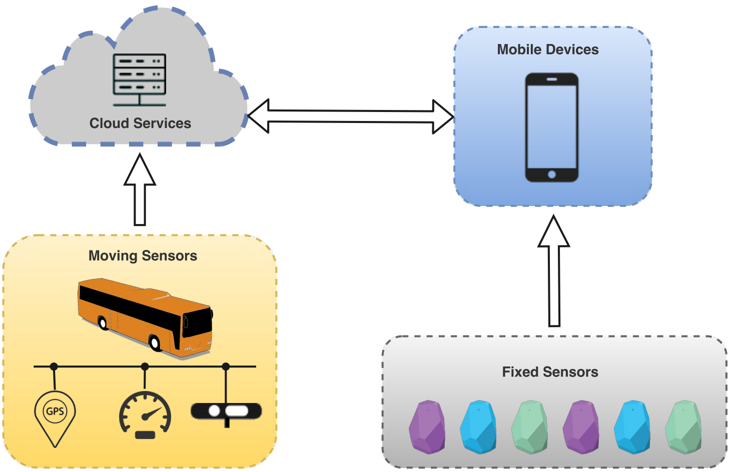


Figure 3.24: System architecture with main components and their connections. AVM sends data to the cloud through a 3G/4G connection. Mobile devices, connected to internet, access cloud services getting buses' info and putting localization data. Localization data are obtained with beacons.

Outside the "festival area", a shuttle bus service was planned for the whole duration of the event. Shuttle buses were equipped with a network of sensors and actuators controlled by an AVM system. The AVM is an on-board computer, with the main task of managing several data of a moving vehicle, both internal and external, such as path, speed, diagnosis etc. It can be connected with:

- opening and closing door event;
- GNSS position;
- vehicle control unit;
- ticket machine (not used for this application);
- intelligent systems of people counting with RGB-D cameras.

The AVM continuously checks the operational status of each monitored component and sends real-time data to a cloud service, via 3G/4G connection, providing information on transport services to the server. In particular, the AVM system processes data recorded by the GPS satellite reception service, allowing the comparison of bus position in relation to the planned service. This provides real time information to users about the expected waiting time as well as estimations about times of arrival at the next stop line of the route [175].

Thanks to a mobile application, specifically designed for the event and available for both Android[9] and iOS[10] platforms, the users had access to real-time data on transport services with a map of shuttle position and forecasts about arrival time. For the purposes of this test, we obtained data about flows of people thanks to the people counting system, performed with an RGB-D camera, installed at the entrance of the bus, in top view configuration. By merging these data with information coming from GPS localization and from security cameras installed to monitor the parking area, it is possible to know incoming and outgoing number of people, without requiring that all visitors have the mobile application installed.

Inside the "festival area", to monitor visitors' movements, we installed an active WSN composed of active beacons, arranged among the urban area of the festival. Active beacons were placed near the main attractions of the festival, with the dual scope of providing notifications and collecting statistics about each attraction. Beacons' ping is caught by the smartphones and the application is enabled to send data to the cloud, specifically designed for the event, via 3G/4G connection. If the device is equipped with the BLE module, it can receive and interpret radio signals from the Beacons. The installed application sends beacon's raw data to a remote cloud repository.

This solution was preferred to other available technologies because it allows the cross-platform development, it has a low cost and it assures a long-life due to low battery consumption. For the set up of the system we used Estimote Beacons[11], which are commercially available sensors with a built-in bidirectional low energy BLE radio. Beacons can be fixed in a pre-defined location and they are able to broadcast the identity information (MAC address, programmable Universally Unique Identifier (UUID), major and minor numbers) to the smartphones around them. Devices into the range of action of a single beacon (between 30m to 70m depending on the arrangement of the spaces) can pick up the BLE radio signal (without previous pairing) and the distance can be obtained with the measure of the Received Signal Strength (RSSI).

However, the operative range of each beacon is computed taking into account several variables, such as material reflections, which are hardly definable a priori. This entails that the disposal of beacons is not based only on linear distance; for the set up, tests were conducted before the event to arrange beacons with the maximum line of sight possible. Push and notification services,

[9] https://play.google.com/store/apps/details?id=it.devq.mogliano.halloween, last access: February 9, 2017

[10] https://itunes.apple.com/it/app/halloween-mogliano/id1051024630?mt=8, last access: February 9, 2017

[11] http://estimote.com/, last access: February 9, 2017

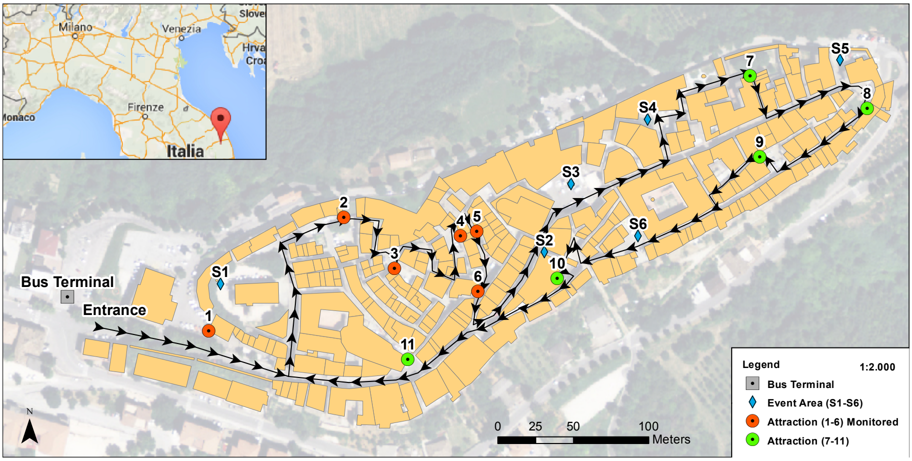


Figure 3.25: Map of attractions and events. The map also reports the positions of bus terminal, event areas, beacons (red circles) used as monitoring tools for a specific attraction, attractions not monitored for the test (green circles). In the upper left corner the location of Mogliano in central Italy.

consequently, were delivered to users when entering into a range of about 40 m.

For this specific case, we performed localization services of mobile devices into the relative system of the WSN. However, the accuracy could be improved by merging this data with GPS or wireless data. For the test case, we chose Mogliano Halloween festival, a theatrical party that lasts for only one night, taking place once per year in the historic city centre of Mogliano town, in Italy. Events and attractions are scattered among the small streets and squares of the old town. Some stages were planned for indoor and outdoor scenarios, other stages took place in completely covered settings like tunnels. Besides, the festival started in the evening and proposed an almost continuous flow of events, many of which at the same time. The majority of the activities in the festival were free, and, starting from the entrance, visitors should follow an "horror" path through eleven attractions (labelled with 1-11 in Figure 3.25). Six outdoor areas (labelled with S1-S6 in Figure 3.25) were planned to entertain parallel events at pre-fixed hours, meaning a concentration of people. This makes the proposed solution even more useful, since the conjunction of parallel events requires a more accurate management of people flows. The configuration of the events, with highlighted the pre-defined flows and the position of the attractions can be found in Figure 3.25.

With qualitative indication of crowdedness from the past editions, thousands of people visit the festival. Furthermore, the path is about 1.5 Km. We arranged six beacons, placing them nearby the attractions right after the entrance. The registration of data started at 8.30 p.m. and ended at 4.00 a.m. Table 3.1 reports significant data about availability of beacon for each attraction and capacity of the areas.

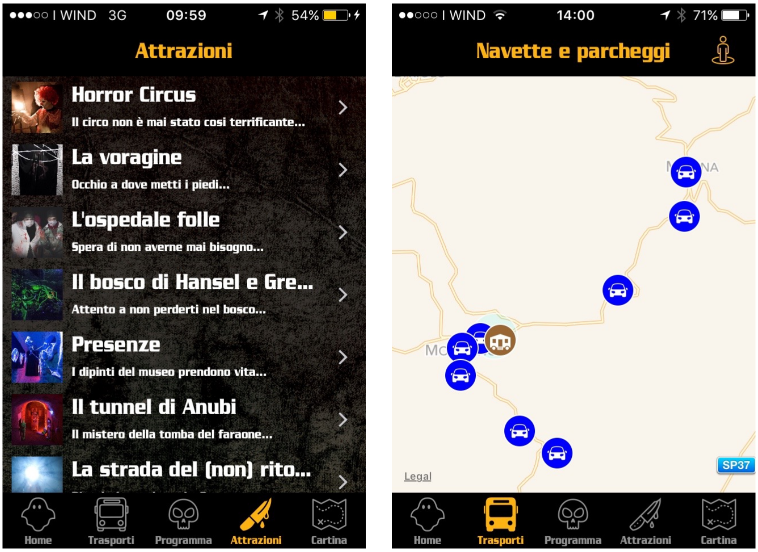
Table 3.1: Location names and installed beacons. For each location it is indicated the area in square meters and the corresponding capacity in number of people (considering a density of 0.4 sqm per people in a crowded event).

Attraction	Location	Area	Capacity	Beacon
1	Zona Halloween Bimbi	500	1250	Yes
2	Horror Circus	400	1000	Yes
3	La Voragine	150	375	Yes
4	L'Ospedale Folle	150	375	Yes
5	Il Bosco di Hänsel e Gretel	50	125	Yes
6	Presenze	150	375	Yes
7	Il Tunnel di Anubi	150	375	No
8	La Strada del (non) Ritorno	100	250	No
9	Il Cimitero	200	200	No
10	Le Segrete di Palazzo	100	250	No
11	Crisalide di Strega	100	250	No
Total		3050	7625	6

Because gathering information from such complicated scenario was challenging, as an experimental setting, we decided to monitor only the six attractions close to the entrance to warrant a more faithful distribution of the data. Besides, we chose attractions close to the entrance (estimated, from the past editions, as the most crowded zone) because they have the major variability of people capacity (the greater and smaller one), being reachable by visitors from different paths.

The mobile application was designed to guide the user among the attractions, giving contextual information about the event. The idea of this application is to use people devices to help optimizing the flows and, accordingly, the fruition of the transportation service. Figure 3.26 shows two snapshots of the application running during the festival; inside the event, with the attractions, and outside with shuttle bus positions and timing of arrival.

As said before, the main functionalities of the application are real time information about the shuttle service and the contextual notification of the attractions. Notwithstanding, other functions increase the user's experience. The localization service allows finding attractions in a virtual map. The list of attractions is useful to reach the one of interest for the visitor; the program was continuously updated to permit a more complete visit of the event. The mobile application, connected with data from the system, drives the user to the next available attraction.



(a) (b)

Figure 3.26: The mobile application running during the event: a) the main attractions. b) the positions of bus stops.

From the cloud service standing point, data were collected in the following way. Once the smartphone is permanently into the operational range of the beacon (recording five consequent pings) the application performs two operations: i) notify the user with a welcome message and ii) send data to the cloud. The same criteria is adopted to discard the device once the smartphone exits from the area of influence of the beacon. In this way we collected a series of information like those reported in Table 3.2. For simplicity, the identifier (ID) of each beacon corresponds with the attraction in the map.

It is worthwhile to underline that, with the proposed application, tracked visitors remain anonymous, avoiding potential privacy infringements. After requiring users of making their Bluetooth devices accessible, movements can be reconstructed only by means of the unique Media Access Control (MAC) address of each BLE device (used as UUID). This fixed MAC address cannot be linked to any personal information such as names or phone numbers, allowing the collection of different types of information only from the mobile devices.

3.2.1.6 Results

We recorded more than 500 downloads of the mobile application, with a ratio 1:3 between iOs and Android devices. During the event, it was possible to collect data from only 50 different devices, that is about 10% of devices enabled

Table 3.2: Sample data record for each tracked device.

Device UUID	Attraction ID	Start Time	Visiting Time
9045A021-...	1	2015-10-31 20:42:44	00:32
9045A021-...	4	2015-10-31 20:50:29	00:49
1DCE3E79-...	6	2015-10-31 20:53:38	13:44
...			
EF0D823B-...	2	2015-11-01 03:42:11	16:42

with BLE technology. This can be ascribed to manifold reasons: not all the visitors used the application during the festival or were not present the day of the event. Above all, the main reason is that, up to now, BLE technology is not sufficiently spread to cover such events, at least in the geographical area where the event took place. Analysis provided from our tests should be considered a useful starting point for similar scenarios, since the Bluetooth SIG predicts that by 2018 more than 90% of Bluetooth-enabled smartphones will support BLE[12]. In the following, the potential of this system is shown, with particular focus on the statistics that were possible after the events. Figure 3.27 reports the number of devices tracked for all the beacons, with a time range of five minutes.

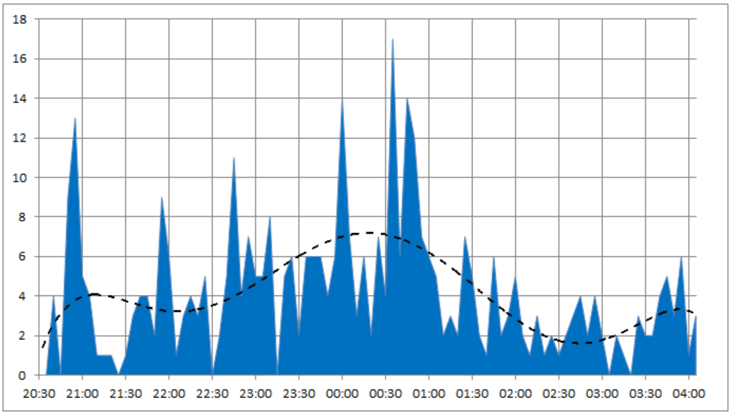


Figure 3.27: Number of tracked devices over time. Tracking data start from 08:40 p.m. and end immediately after 04:00 a.m.. Data are aggregated over time every 5 minutes. Trend is represented as a black dashed line.

Devices were tracked also with the application running in background. The general trend of the graph is growing until 00:40 a.m. and decreases constantly

[12]https://www.bluetooth.com/marketing-branding/markets/mobile-phones-smart-phones, last access: February 9, 2017

until the end of the festival. The initial peak is probably caused by an initial usage of the application by the first visitors to discover the list of attractions and then not used during the visit. We also calculated the crowdedness at a location over time, aggregating the number of detected phones over regular time periods. Furthermore, by grouping subsets of attractions, it is possible to estimate the crowdedness for wider areas. For this case study, we made statistics by computing the visiting time for each beacon, reported in Table 3.3.

Table 3.3: Locations with installed beacons. For each point of interest average visiting time in seconds and number of people passing.

Beacon	Number	Min	Avg	Max
1	30	00:24	09:20	57:28
2	26	00:31	03:23	33:56
3	14	00:33	01:18	02:37
4	12	00:41	02:34	16:35
5	4	00:31	01:53	04:30
6	18	00:11	10:34	45:25
Total	104	00:11	05:55	57:28

It was possible to perform an estimation of the number of people passing in the range area of each beacon, reported in Figure 3.28. This estimation, calculated from our dataset, corresponds to the estimation made by the city department; the most crowded attractions were positioned in the wider squares. In this way we had the possibility to extract some features and patterns from the visitors; in some points people were only passing through. By matching this information, we can deduce that some areas were crowded for long periods. Even if the number of samples is low respect to the total number of visitors, it is possible to notice natural trends of people moving around and inside the urban event. This highlights the suitability of Bluetooth tracking for studying spatio-temporal crowd density variations for predefined areas. The experimental setup should be increased in terms of number of beacons and tracked devices to reach a statistical meaningful sample, to perform statistical inference for a wider set of data and to achieve a reliable clustering of people.

3.3 Senseable Spaces and Geosciences

In the previous section, we examined the POS domain, a particular kind of space designed for the specific objective of encasing human lives; the space was made *Senseable* thank to the use of specific sensors (active beacons) able to interact directly with the mobile devices. From this, arose a good solution to use UGD for a better understanding humans dynamics and for planning purposes. But exist also other kind of spaces, like for example the landscape at a territorial scale, that could really benefit from the proposed approach. The ability to use GPS receivers, remotely stored information into GIS platforms and connections to upload new information will contribute to make the maintenance of our landscape more affordable; in the following, we demonstrate how natural environment (made of hillsides, rivers, basins and more) can become a *Senseable Space*.

In the general context of nowadays-environmental crisis, the key challenge for modern agriculture is twofold: on one hand, there is the necessity to feed many billions of people. On the other, the preservation of good quality conditions is compulsory. Accordingly, the quality of fresh running and underground water is a key issue [176]. In the agricultural landscape and over wide rural territories, the modern approach of water protection is based, among others, on the use of linear Buffer Strips (BS) along watercourses. These conservation buffers are small bands of land in permanent vegetation, designed to reduce the run-off, the accumulation of bank-top sediments and the leaking of pesticides into fresh-waters. These vegetated strips benefit the overall quality of surface

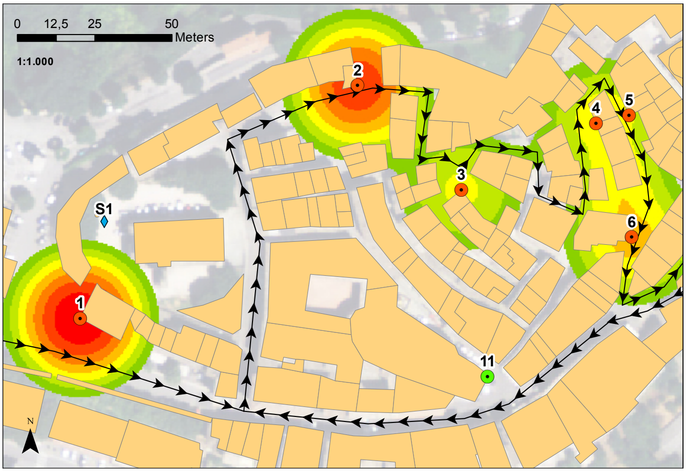


Figure 3.28: Heat-map of people passing. Red area around beacon indicates a higher number of tracked devices.

waters reducing the potential impacts due to agricultural activities and other sources of pollution [177]. As a matter of fact, buffer strips play a set of positive functions, such as: pollutant adsorption, riverbank stabilization, micro climate improvement etc. To achieve effective protection, it is well known that the network of vegetated strips must be designed with a carefully installed and well maintained stringent scheme. The protective network needs to comply with two main conditions: the integrity of the spatial continuity of the protecting belt and constant man-hours of maintenance of riverbanks. The monitoring over a wide network of vegetated linear features, whose pattern stretches across thousands of miles, is a hard task. Despite the potentialities of GIS in managing geo-datasets and delivering relevant thematic maps are well known, the use of specific applications is still broadly missing; indeed, geographical visualization of wide datasets directly in the field require costly and specialized equipment. A significant improvement of the environmental monitoring and control can be achieved by adopting effective management strategies to increase the awareness of risks ([178]; [179]). The possibility of taking sound strategies depends by the amount and by the quality of the information available for all the people involved in the management and control-chain. The visualization of geographic data is a suitable approach to enhance communication during decision-making processes [180]. In particular, viewing the physical real world "augmented" by computer-generated sensory inputs represents a powerful tool to deliver supplementary information about the surrounding environment and its objects, enriching the human perception. This kind of visualization can be achieved using AR, that could trigger smarter watershed control and riverbank maintenance with less time-consuming during on-site inspections; furthermore, it can be used to cope with the technological limitations that cannot be overcome by using GIS as a stand alone platform. By merging these technologies into a single platform, data become available in real time. The main actors who can benefit from this are the on site inspectors, that have at their disposal a quick and agile tool for monitoring and updating tasks, and the managing authorities, who can remotely check the data collected on site in real time.

3.3.1 Smart maintenance of river banks with the use of Augmented Reality

The environmental management includes the monitoring of specific areas to understand the changes and the evolutionary dynamics. The mobile environmental monitoring has proved to represent a promising field of application for mobile devices [181]. Such an advanced method of environmental monitoring could represent a key approach to re-interpreting the concepts of monitoring and maintenance. Certainly, on-site inspection is a base need for planners and managers. Information collected during field surveys allow a deep understanding of reporting areas. Environmental officers and other land management authorities usually perform on-site inspections, during their daily work, for monitoring changes, designing activities, searching for patterns or for better understanding the specific existing conditions. Nevertheless, the practice to manage the environmental processes by paper plans, which are plotted as needed and manually annotated on a construction or maintenance site, is still widespread [182]. Therefore, the environmental data analysis process needs the introduction of technological tools to make more effective and reliable the monitoring and maintenance phases [183]. These tools should considerably improve on-site inspections to assist authorities in the narrow implications with environmental changes; in this way, the process of context understanding should be improved and the solution easier to find. These considerations entail addressing the entire process of environmental management toward the mobile approach. On-site work remains the only efficient link with the office work, because it allows the gathering of self impressions and an aware method of data processing. Nowadays, on-site work means mobile devices and activities always involve the use of different hardware devices, especially because they are increasingly portable and less expensive. On-site activities do not replace the office work but they have become mandatory for the entire workflow of an environmental analysis. Furthermore, mobile devices are equipped with sensors that help user in orientation and navigation and, above all, they network the devices, and hence the user, with the real world. The introduction of the user location, everywhere at every time, leads insiders and developers to rethink the mobile approaches in a new manner, meaning that applications would tend to always put in contact the user with the real world. The challenge is to find the best way to exploit the system potentiality since the most important thing for risk managers is the visualization of data. Considering the needs of a geoscientist (e.g., availability of data, intuitive tools, reducing inspection time), the challenge is to make GIS data suitable for mobile environment (e.g., visualization for monitoring), exploiting the metadata intrinsic with the GIS objects and necessary for their geo localization and visualization. GIS and visualization systems are both approaches to discovering and understanding patterns and issues found in geospatial data [183].

Sensor-based AR could be considered very suitable for landscape monitoring [184]. Thus, all the sensors embedded inside devices should cooperate simultaneously to visualize supplementary information as part of the real world. Furthermore, once data are displayed, the user is able to interact, to update, to upload, to share or to modify data during his or her investigation of a specific area. The cycle of work is explained in Figure 3.29. To perform a monitoring task, in addition to object visualization, the system must be able to guide the user toward the real position and, when arrived, to recognize it in the real environment. Only under these conditions, an accurate analysis and correct control activities will be possible.

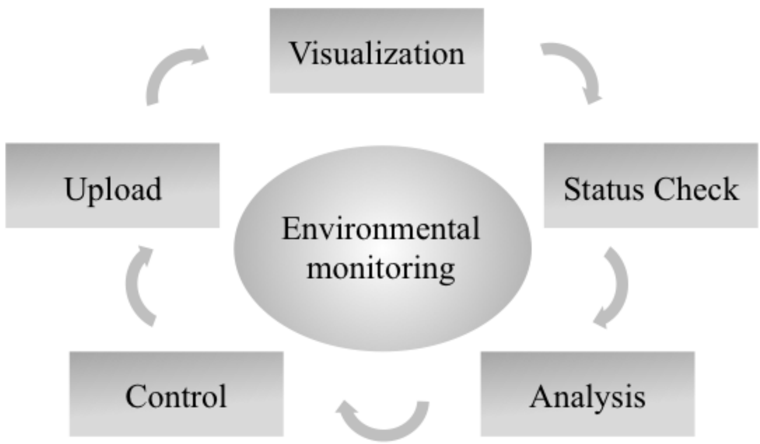


Figure 3.29: The cycle of environmental monitoring: the process starts with the AR visualization of GIS data and can be endlessly repeated since the app is directly linked with the server.

Even if virtual objects often help the user to simulate the reality (superimposing items that blend into a mixed reality), we consider the visualization of GIS data as particularly suitable not so much for enhancing the reality perception but for helping risk managers during on-site inspections. It allows the user to walk around and observe the environment, continuously getting a "correct view" on sensor data, since information overlapping gives the possibility to improve the knowledge of the real world. The AR technology strives to render computer-generated artifacts correctly blended with the real world in real time. These artifacts appear in the correct position relative to the point of view of the user. Furthermore, interactive visualization enables the communication and the exchange of data (e.g., images, data, graphs) between an on-site observer and decision makers. In fact, end users are expected to have a better view of the global situation before, during and after an event by adopting image overlay techniques depending on the user's location.

Whereas AR is widely spreading its usefulness for a variety of outdoor applications, the usage of AR in environmental monitoring is quite novel [185].

The application proposed in the following is novel itself, and it is built over a novel data layer that could be used as a standard and common way of describing riverbank maintenance toward a consistence standard data layer. The whole pipeline goes from satellite images, to GIS-ready data, to cloud based services, until AR user interactions. Finally, we performed on the experimental test bed, based on real user experiences and real data, providing a powerful contamination experience between computer scientists and geo-scientists.

3.3.1.1 Scenario: monitoring river banks buffer strips

This case study is particularly suitable for the visualization of information on mobile devices; vegetated BS are constantly evolving because of the sudden growth of surrounding vegetation and because riverbanks are continuously changing. Besides, since BS are disseminated among wide areas, on-site monitoring is a challenging activity. Given the above, the only way to ensure their correct maintenance by the owner is on-site inspection using tools that can identify the POI in the correct location in the real world. In this light, our purpose is to provide management authorities, land managers and insiders with an intuitive and dynamic real-time visualization tool. The proposed solution combines an existing GIS with the use of relevant AR technology. We have designed an experimental data visualization test to encourage land managers and other potential users to perform more advanced monitoring and management practices. More in depth, we have outlined a novel approach to the way in which officers could perform the health-check of linear vegetated BS protecting riverbanks. The GIS coverage, which usually builds the base of reference for the auditing and for the on-site inspections, has been enriched by AR driven information on the position of targeted features, environmental state, degree of pollution, etc. within the reporting area, at river basin scale. From the technological point of view, the system architecture is made of a cloud-based service for data sharing and of a mobile application using a GPS-based AR engine for augmented data visualization using smart phones or glasses. On the one hand, GIS allows for managing, modelling and maintaining relevant amount of geo-data, delivering suitable thematic layers. On the other hand, AR enriches the geo-layers with a real-time visualization on-site. In this way we increase and improve geographic information management, whose readability becomes more explicit thanks to the connection between the real world and its modelled representation displayed by thematic maps. Such new forms of enriched or, better, augmented geo-information reduces the efforts in operating a mental transformation from map to reality [182]. In turn, this enables users (i.e., managers and field-workers) to interact in a more intuitive way with risk maps and management plans. All that is of particular importance for field workers, because using GIS-based AR services would help risk control surveyors by reducing the operational time of surveying, as well as improving the access to relevant information not always available during field campaigns. Within this frame, a previous research delivered a suitable geo-database and tested a multi-scale GIS approach to determine the optimal type and location of buffer strips, at both parcel and collection level, and to investigate their adaptability to the Marche Region. The work by the Division of Earth and Environmental Sciences at KU Leuven in Belgium [186] delivered a GIS model to support land managers in deciding the best alternative Buffer Strip typology, starting from given spatial conditions. Floodplain maps, land use maps, erosion maps, DEMs, etc. were used to accommodate the best allocation of buffer strip typology. The model has a parametric iterative decisional tree structure, made of two sequential sub-models: the first one sets the pre-conditions that define and split the problems into different layers; the second sub-model classifies lands (usually parcels) assigning specific buffer strip categories according to outcomes of the above iterative sequence. The adaptation of the model to the Italian conditions was possible thanks to the contribution of an Italian team [187]. In particular, land use maps were updated thanks to a hybrid Land Cover Land Use (LCLU) classification by high spatial resolution multispectral imagery and LiDAR data [27]. As shown in Figure 3.30, a set of features buffered along watercourses are generated. In this context, our purpose is to take advantage of a new solution assigning buffer zone to specific areas, adjacent watercourses, and turning this information in an AR environment. This solution enables to visualize buffer strips as geo- layers in the physical world thanks to AR.

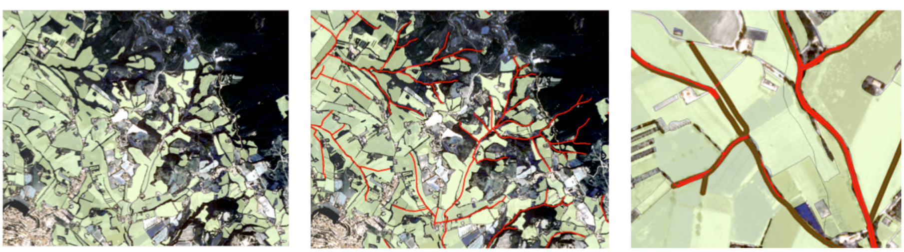


Figure 3.30: Case study area viewed on WorldView 2. Left: assignment of each piece of land along the water courses to a specific buffer strip typology. Center: buffer strips built by buffering parcels according to a given distance from the river streams (red). Right: detailed view of intersections between classified parcels and buffer strips.

3.3.1.2 System architecture

The visualization of buffer strips directly on-site is fundamental; as a matter of fact, farmers who want to step-up into the Common Agriculture Policy funding scheme and claim for the payments of subsidies, must compel with a set of conditions (Good Agricultural Environmental Conditions), among which the maintenance of vegetated strips (BS) along watercourses is compulsory. Local authority has to ensure that the network of BS is kept and maintained over the time by the farmer. The faster way to monitor the operational state of the network is to identify the linear pattern and verify its maintenance status. In the following section a mobile AR application for GIS data visualization is described. Our tool provides the necessary information to properly inspect the area of investigation and to visualize in real time the BS. Buffer strips are contextualized within the real environment once the camera is on and placed in the correct location where they are located in the GIS cartography. The purpose is to provide a geo-visualization method for real time and on-site data visualization, particularly suitable for this case study, but that could be used for many other GIS datasets. Details of the development phases, libraries and functionality of the application are presented in the following section.

3.3.1.2.1 From GIS to AR environment To move from GIS model to AR Geo-layer, we designed a workflow based on several items. Starting from the decisional model previously described, are needed:

- availability of geo-referenced data from the GIS;
- contents to be overlaid once the user is on-site;
- a tracking system;
- link to sending data to the cloud
- interaction with the superimposed contents.

The first part of the workflow consists in translating the polyline shape file (“shp”) of the BS and all related files (“sbn”, “sbx”, “shx”, “dbf”) to “kmz” or “dxf” exchange CAD formats. For the AR experience in-situ, the visualization of a 3D model is preferable, so we extruded the “shp” polygon importing it into a three-dimensional modelling program (e.g., Sketch-up); once the model is imported, the user can apply every required changes (e.g., material, color, extrusion, and so on). The next step is to edit this model by Layar3D model converter, a powerful tool which enable this transformation; the most suitable format for this kind of operation is the “.obj", because of its capability to maintain the original file object and the possibility of being edited. In this phase, it is also possible to geo-reference the model on a common Open-Street Map environment. The final output is an "l3d" file, which can be defined as a geo-layer ready for being uploaded to a web-server. For a web based implementation, a Relational Database Management System (RDBMS) is necessary, as well as a classical web-server which hosts php pages. For this test we adopted the open source MySQL server. In the database we built a table that contains data regarding the Points of Interest (POIs), geometrical transformation, description and link to external resources. A web service is needed to fetch the POI information (in JSON format) and get it back to the AR platform. The POIs are stored within the database by exploiting the same architecture described in Sections 3.1.2.5 and 3.2.1.2. These parameters are computed by the application, permitting to overlay the virtual model of the buffer strips into the real scene. To retrieve these points at user's request it is also necessary that the application generates a php script that returns the POIs. In order to visualize only a subset of buffer strips, we set a radius of influence limited to 1 km from the user location. Within this radius, the application looks for relevant POIs. At this stage, the last step to complete the workflow is to perform a series of asynchronous calls to activate the php script, which is possible from any operative system, passing the user's location coordinates as parameters. Figure 3.31 is an explanatory scheme of how the architecture works. From this point the mobile app can interact with the contents captured from the RDBMS.

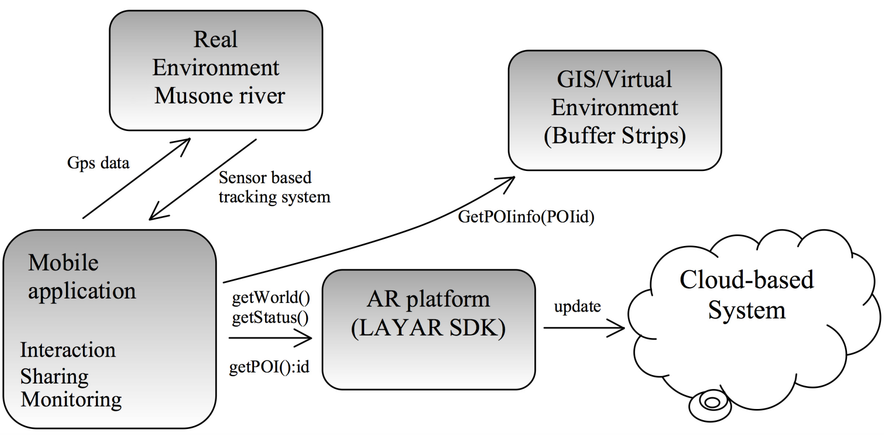


Figure 3.31: System architecture diagram and test-bed.

3.3.1.2.2 Standard Data Layer and Mobile Application The developed application has been designed to allow the user to complete the following tasks: to interact with the buffer strips, to update comments, to send reports and to give users the possibility of localizing POIs. The data structure of the whole architecture is summarized in Figure 3.32.

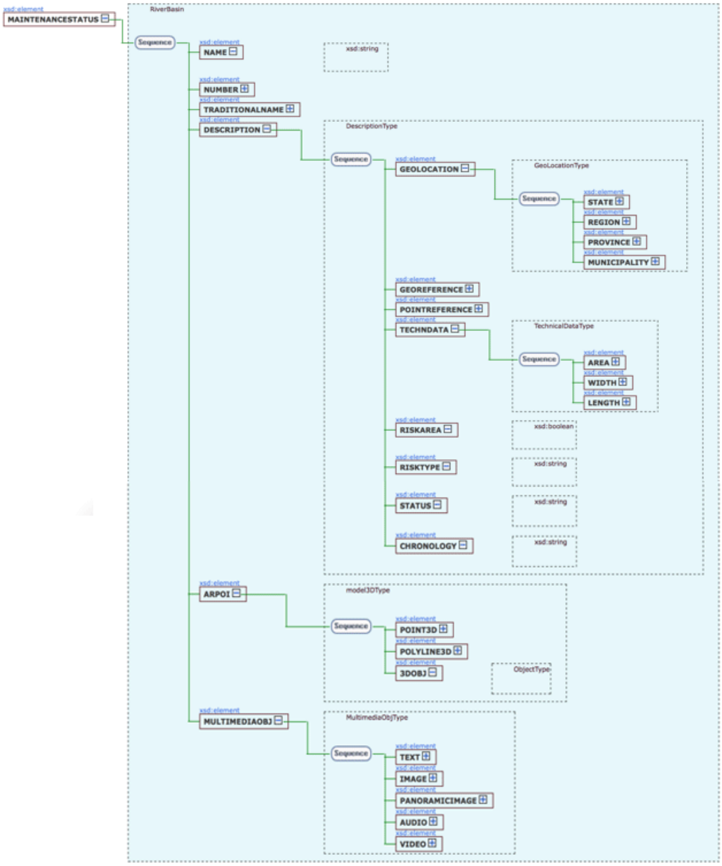


Figure 3.32: Standard data layer architecture of the main system, with the data structure of every components.

The data layer describes the following components of the XSD element named MAINTENANCESTATUS:

- Identification data: are used for textual and id identification of the maintenance POIs, use a short name (NAME), an id number and a long name (TRADITIONALNAME)
- Description data (DESCRIPTION): are used to describe the maintenance POIs and uses geolocation, identified by an international standard address, the maintenance area (TECHDATA), the identification of this area as a risky one and every detail about the risk type, the status of the risk,

etc.

- AR data (ARPOI): are used to show in AR all the spatial information superimposed to the real scene, using the LayAR standard description for points, polylines and shapes.
- Multimedia data: are used to add multimedia information to the POIs. Every virtual layer can be enriched by the user, who can link to the POI his own content related to it (e.g. tag, text, images, panoramic images, audio and video contents). All this data is a part of the proposed standard and detailed description con be found on the project web page.

The application has been developed also considering the usability user test described in Section 3.3.1.3, which permitted the development of a user friendly interface. Besides, as per users suggestions, we also implemented a caching service giving the possibility to operate without network connection. The main functionality of the application are listed below.

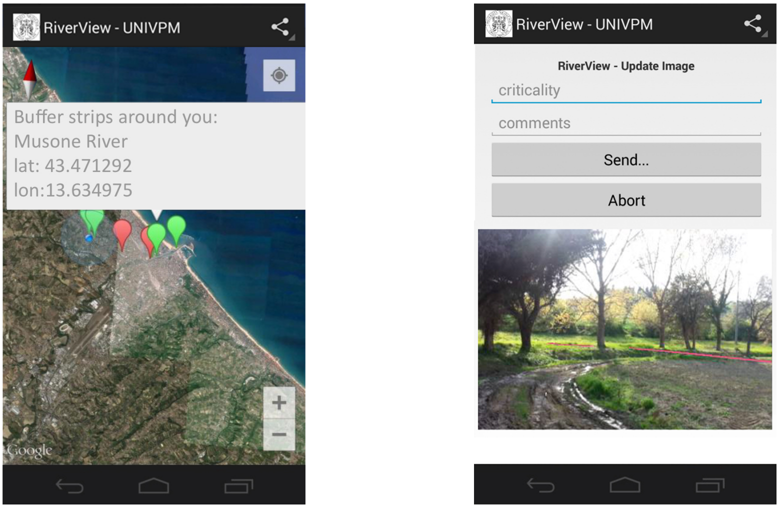
- Augmented reality tool:
  this functionality allows the user to exploit the augmented reality browser to search for the buffer strips closer to him/her. The compass, displayed on the screen, visualizes the nearest one; in this way the user can easily reach the area where the strip is located. To implement this feature we took advantage from the set of embedded sensors of mobile devices e.g. compass, gyroscope, accelerometer and GPS receiver. For adjusting the search area , the user can set a search radius from the device. This is particularly helpful during the campaign to retrieve information of a limited set of POI nearby the user. As default, the radius value is 500 m. Moreover, the application allows obtaining more information by displaying in a pop-up window the title, description, footnote and the image associated with the POI selected, as well as the BS typology. All these features have been implemented by using libraries provided by API LayarSDK: a static library that implements augmented reality and geo-localization functions. Fig. 3.33 shows an example of AR applied to river basin on the study area.
- The use of the map:
  the map function is a key tool to have a quick overview of all the relevant POIs of a specific area, keeping trace about previous comments associated to it. The map module was designed to expedite the inspection; in fact, it helps to immediately identify the BS distribution and assists in understanding the nearby environment. Thanks to the map visualization, the user can quickly reach the complete set of information such as typology, length, coordinates and all data stored into the database regarding BS

Figure 3.33: Screenshot in landscape mode, taken during on-site inspection. On the upper side, the radar guides the user among the countryside towards the POIs. The red line is the buffer strip that appears automatically when the user gets into the radius of influence. The lower side shows the strip typology, the metadata arising from the GIS database.

(see 3.34). These functions were implemented using the Google Maps V3 API.

- Management of Points of Interest:
  each time a specific buffer strip is selected by clicking on it, users can choose between two alternative actions: to “add a comment" or to “enrich" the scene with AR contents. The first one allows to report relevant information about the specific POI by simply posting a comment, or to mark any potential issue affecting a specific strip feature. Being stored into the remote server, these comments are suddenly available in GIS-ready mode. The second option allows users to enrich the scene by enhancing information with all comments regarding a specific POI. This function helps surveyor in making critical choice during the trip and also to easily retrieve all the information once he is back at office (see Figure 3.34).

- Data Management:
  this functionality copes with the need of updating POI comments also in case of lack of network connection; data are locally stored into a mobile device (i.e., tablet or smartphone). A structure containing the local database and a POI table were created in order to add, to read and to update POI locally. A suitable class is created to manage the POI data



(a) (b)

Figure 3.34: a: POI visualization on the map. b: Real time visualization of buffer strip (in red) with the possibility to share information or comments.

structure within the local database. The Database class is used each time a user needs to store a comment or a related file (i.e. a picture) in offline mode. To upload local data into the remote database a specific class is instantiated every time an item of the application's main menu is selected: it checks if the local database is empty, checks the network connection and, in case of affirmative result, uploads the local data to the remote database.

3.3.1.3 Results

We have designed different test cases under different conditions. The tests were made in real scenarios, at a latitude of 43°33′36″ and longitude of 13°30′05″ with different daytime, mainly focusing on the usability and positioning accuracy. During the testing phase we observed that the application retrieved and displayed the buffer strips in less than a second. The system proved to be responsive to user commands, having a quick access the database. Furthermore, all the 3D models linked with the GIS system where displayed correctly in the landscape. For evaluation the usability we have tested the system with subjects involved in the environmental management such as: planners, landmanagers, officers and practitioners of different age. To make up the panel of expert involved with the planning and management of the environment for the tests, we also gathered information about their habits and technological skills.

Even if the sample of practitioner were not skilled in the use of technology they appreciated the system. Almost all users didn't know AR but appreciated this technology. The majority of the sample (70%) retains that similar applications are necessary resources to improve monitoring activities. They have generally found that the application is simple to use, although with respect to the general idea, they suggest the improvement of the relationship between the GIS platform and the mobile application. For testing the accuracy of the tracking system, we tried different 3D models of the buffer strips, in different locations and times. The devices used in our test were an iPad 2 and a Samsung S3. The system is also compatible with LayAR for Google Glasses. With the overlapping of several screen shots, we checked that the positioning of the virtual contents were stable and visualized in the same position for both devices. With the GNSS service available, accuracy was between 5 m up to 10 m, depending on vegetation canopy coverage. By the way, the accuracy of the superimposing of digital contents is strictly dependent on the current accuracy of consumer grade GPS receiver. The current state of sensor-based and marker-less AR technology is mainly limited by positioning accuracy; moreover, the spreading of geospatial applications will depend on the growth of the customer market for more accurate positioning systems. Despite the system architecture is complex, we have designed a simple user interface (UI) to ease user's approach. In this way it is possible to cope with all potential difficulties that users could face during the work on field, such as bad weather conditions or impervious accessible areas. The more intuitive is the UI the faster the inspection will be. It is important to highlight that the developed tool can serve monitoring and maintenance tasks at the same time. In fact, the proposed solution, besides allowing monitor and supervise reporting area (in our specific case, the buffer strips at collection basin scale), also allows to share observations and surveyed data in real time, by uploading and linking this information in a GIS environment. In particular, the cycle shown in Section 3.3.1 can be re-iterated endlessly: the health-check status of buffer strips can be monitored and verified at any time and the environment constantly maintained.

3.4 Senseable Spaces and Retail

The specific domain of Retail Environments deserve a focus of attention; because of its nature of being an attractive space for humans, the *Senseable Space* paradigm get an increased meaning. The design of a point of sales, the monitoring of its performances and also the capability to engage customers attention are, up to know, the most important challenges the Retail sector is facing. But it is important not to forget that the spatial dynamics we described in the previous section, brings always to the same added value. Give information to the users (the customers) and get information to them for planning/decision making (the retailers). Heading all these assumption, there is the data collection task, that is to say measuring what is really happening in a space (the store). “Measure to design”, “measure to react” thanks to the help of Ambient Intelligence (AmI). The key aspect for AmI into retail environments lays in the possibility to provide services not only guided by user request, but also based over the intelligence of the system; this will allow the automatic provision of services depending on the profile and the position of the user inside the store. Consequently, the interaction between spaces and consumers should be done through natural interfaces adapting to their habits and behaviour. Nowadays, this process has been enhanced thanks to the tremendous improvement of sensors, actuators and processing units that are increasingly cheaper and smaller.

Development and standardization of new low power consumption and short range wireless technologies have led to novel pervasive computing concepts. In this scenario modern active beacons or wireless sensors presents many advantages such as flexibility, adaptability and less power consumption [11]. Today, there are several options for the development of a pervasive computing environment and a variety of scenarios between standards and technologies can be found [188].

We have seen how mobile devices are employed in all areas of science; literature and real case histories demonstrate how pervasive computing enhance benefits for retail; this is true for consumer as well as for retailers [189]. In the last decade we observed a turnaround in the concept of shop. One time it was only the place for searching and buying products [190], nowadays it has become the place where consumers spend time, test products in real time or just inquire about the recent products or trends. People inside the stores are guided not only by the prices, but also by the ambiance of shopping, professional consultation, seeing, touching and product trying [191]. Because of this, the research about consumers' behaviour are strictly related with in-store features for the retailers.

3.4.1 Intelligent Retail Environment

Localization and people tracking in an indoor environment (e.g., stores, museums, hospitals, public and private buildings in general) is an interesting challenge for AmI applications. If the location of monitored subjects is well known, a smart system can provide them with correct and proper information about the surrounding environment.

In a localization system, accuracy and precision are parameters that depend strictly on the intended use of tracking. Accuracy is the mean error distance, and the precision is defined as the success probability of position estimations with respect to predefined accuracy [192]. A localization system is also classified based on other parameters such as system scalability, coverage area, cost and capacity [193].

There are numerous localization approaches for indoor environments suited for many use cases, showing different characteristics in precision, complexity and accuracy. Taking into account the study conducted in 2008 by the National Institute of Standards and Technology (NIST)[13], the main characteristics required by a communication and localization system can be summarized by the following specifications: (i) precision of localization of about $1m$; (ii) functioning properly within all types of buildings; (iii) no site-specific training required; (iv) stability against structural changes; and (v) moderate costs. We can also find a similar list in a report of the Worcester Polytechnic Institute[14].

According to Wendeberg et al. [194], localization systems based on Time Difference of Arrival (TDoA) have the great advantage that the target must only emit a signal without cooperation with the receivers. In their paper they estimate the trajectory of a beacon device moving in an indoor environment and emitting short signal bursts received from multiple receivers distributed in the environment. In contrast with most of TDoA localization systems, they used the particle filter method and a Gaussian distribution to measure the errors, by filtering the multiple positions of the moving beacon. Knowing in advance the positions of receivers, many approaches have been used to solve the problem of localization and tracking of signal beacon: iterative methods with squared (or maximum) likelihood estimators, linear estimators [195], particle filter [196], or Kalman filters [197].

For indoor localization the main common approaches are based on received strength of radio signals, by evaluating the Received Signal Strength Indication (RSSI) of stationary satellites used to evaluate distances [198]. In literature there are many uses of RSSI for several systems of position estimation [199]. An important aspect is to develop algorithms that can filter several position information derived from multiple sensors. Some of these methods previously introduced, such as Kalman filter or particle filter, improve the localization accuracy. The choice of using one filter rather than another depends on the type of sensors used, the available power of processing and the given environment. Another possible improvement is to combine different fusion filters by exploiting multiple data sources generating a more precise tracking. In literature an application of this method is proposed in [200], where the Kalman filter and particle filter are combined by obtaining a more accurate estimation of the trajectory detected by the tracking system. Our approach is based on distance evaluation from received of strength radio signals of stationary bea-

[13] www.nist.gov, last accessed: February 9, 2017
[14] www.wpi.edu, last accessed: February 9, 2017

cons, enhanced by Kalman filtering as technique to combine data from RGB-D camera.

3.4.1.1 Scenario: customer profiling by vision and radio beacon sensor fusion

The main purpose of the project is to evaluate, in a not empirical way, the success of marketing strategies, investigating over the decision-making process which drives consumers towards choices. The aim of the proposed solution is to provide retailers with useful information, analysing consumer activities inside the store, made "intelligent" with a WSN based on Active Beacons and RGB-D camera. A network infrastructure that allows processing the context through the user interaction in real time [10]. Our approach is based on the interaction between mobile devices and smart Bluetooth Low Energy (BLE) antennas for indoor localization methods, mapping the customers to the floor plan and making spatial/temporal statistics. Although BLE beacons are useful [201, 202] for retailers in terms of customer analytics (i.e., consumer attraction, most visited areas, groups inside the shop, etc.) and revenue improvement, our test demonstrate that provided indoor localization is error-prone. For this reason we combine other sensor data (RGB-D camera) to enhance position estimation, making this system more affordable and accurate. On the one hand, RGB-D camera provides a higher level of precision for limited areas and, even if low-cost for the single unit, the coverage of the whole shop floor would be expensive. This aspect makes the use of RGB-D cameras suitable for specific areas such as entrances, cashing boxes, shop windows etc. On the other hand, active beacons have lower precision but they cover a wider operational range. The proposed solution is based on a sensor fusion, in order to exploit the best features of both sensors. The main contribution lays on the multi sensor integration based on different technologies that are usually installed in modern retail environments (cameras and beacons) and that alone are not suitable for a comprehensive and precise people tracking: from one side beacons are not precise enough to correctly analyse people behaviours, while from the RGB-D camera point of view a full coverage of the store is not economically affordable. The research described in this scenario demonstrates that this multi-sensor fusion technique is suitable and results coming from real test in a retail scenario are satisfactory. Other novelties are introduced: the action-reaction data scheme and the ability to scientifically prove effectiveness of communication and general "call to action" in intelligent retail environment. Finally we tested also a simple Human Behaviour Analysis (HBA) approach able to classify users' behaviour, with the goal of designing a proof of concept of the whole data flow going from sensors to tracking and from semantic maps to consumer behaviours.

3.4.1.2 System architecture

The proposed system architecture consists of an active WSN, arranged among the store, composed of active beacons and an RGB-D camera. The user's smartphones, with a BLE module, can receive and interpret radio signals from beacons. The installed application sends Beacon's raw data to the server that compute Kalman filter with position estimation received from RGB-D camera. The server can provide this more accurate localization to the smartphone allowing also a more precise context awareness. A schematic explanation of the whole system can be found in Figure 3.35.

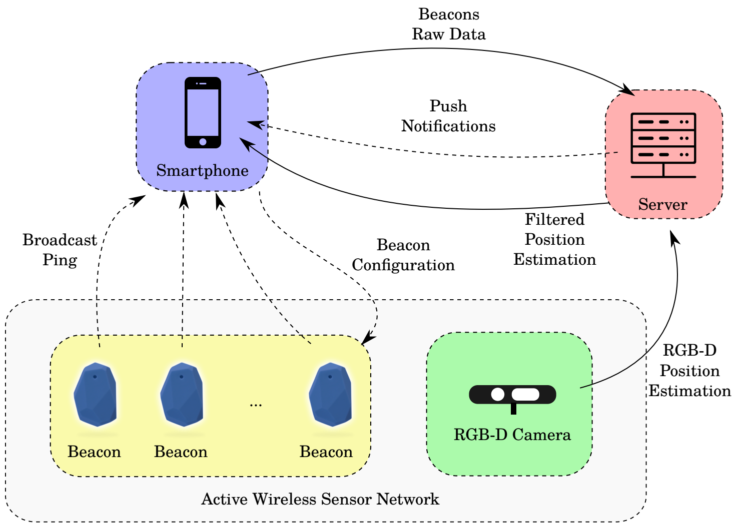


Figure 3.35: System architecture with main components and exchanged data.

Beacons have been preferred to other available wireless technologies because they present many advantages such as cross-platform development, low costs, long-life (thanks to low battery consumption), simple installation in the store and compact design. For the set up of the system we have used Estimote Beacons[15], which are commercially available sensors with a built-in bidirectional BLE radio. Beacons can be fixed in a pre-defined location and they are able to send the identity information (MAC address, programmable UUID, major and minor numbers) to the smartphones around them, implementing a broadcasting service. Devices into the range of action of a single beacon, between $5m$ to $70m$ depending on the arrangement of the spaces and broadcasting power (configurable from $-30dBm$ to $+4dBm$), can pick up the BLE radio signal (without previous pairing), and the distance can be obtained with the measure of the received signal strength (RSSI). To achieve a better customer experi-

[15] www.estimote.com/, last accessed: February 9, 2017

ence, as well as a more affordable data analysis, the signal frequency can be switched between 1 times ($1Hz$) to 10 times a second ($10Hz$), increasing the battery consumption. Beacons are also configurable to transmit tiny amounts of information, hence contents (e.g., texts, pictures, etc.), implementing a light push/notification service. To deliver more context information, the mobile application can query a device-stored database or retrieve data from a web-service on a server or cloud-based storage space.

The mobile application represents the crucial node of this AmI architecture, acting as the linking element between the space, the customer and the information. The Estimote SDK allows to manage intercepted beacons' broadcasting ping. The environment is described as JSON map file containing both space boundaries and beacons' position (identified by MAC address) in Cartesian coordinates, as presented in Figure 3.36 right.

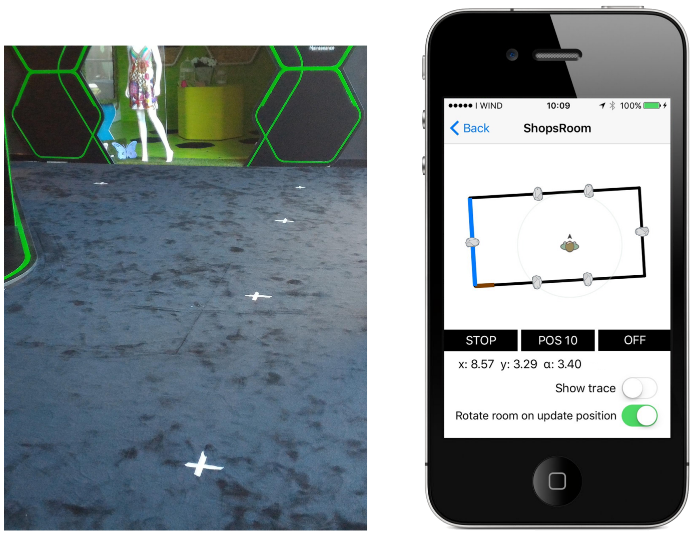


Figure 3.36: Indoor localization application. On the left a picture of the showroom with marked ground-truth points. On the right a screenshot of the mobile application, based on Estimote SDK with developed additional functions, to send raw data to the server and to visualize compass orientation and received relative coordinates.

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The application receives (with a frequency of $5Hz$) raw data (beacon's MAC address, broadcasting power and RSSI) and calls the server method of the developed RESTful API (Application Programming Interface), to get device position. This *"Beacons raw data"*, sent to the server in JSON format, are stored in the database with *ApplicationID*, `DeviceMACaddress`, *EventTimestamp* and `DeviceOrientation` (read from built-in compass).

In the meanwhile, an RGB-D sensors system is configured to control an area and to track people, identifying (see Figure 3.37) and sending position data (*"RGB-D position estimation"*) with `CameraID`, `PeopleID` and `EventTimestamp` to the server. To implement this service we used same protocol and interface of the mobile application, whilst position data are obtained using method proposed in [203].

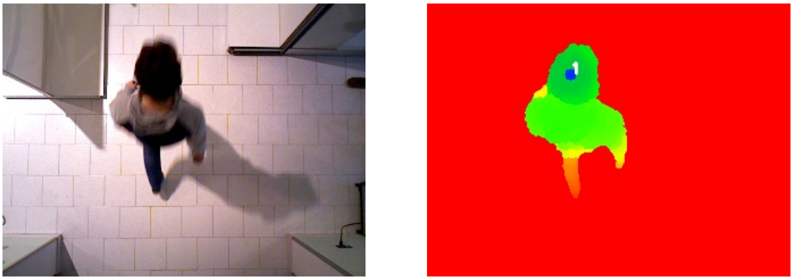

Figure 3.37: RGB-D sensors system. On the left the top-view RGB image of a person walking inside camera coverage area. On the right the depth image of the identified person labeled with `PeopleID`.

The server uses *"Beacons raw data"* to estimate the position of the device using signal attenuation lateration technique, localizing the device with relative coordinates (*"Beacons position estimation"*) using an environment description (JSON map file provided to the application). The server combines *"Beacons position estimation"* and *"RGB-D position estimation"* applying Kalman filter to obtain a more accurate localization, named *"Kalman position estimation"*, as outlined in Figure 3.38. The *"Beacons position estimation"* and the *"RGB-D position estimation"*, respectively identified by `DeviceMACaddress` and `PeopleID`, are combined matching device and people by coordinates, timestamps and tracked movement. Computational time is shorter enough to provide this position back to device in the server's response with application-dependent information (e.g., notifications, special offers, discounts, fidelity invitations). Application can use this new position and information to query local database or server/cloud service to retrieve contextual content in a sort of spatial/semantic way.

This *"Kalman position estimation"* is the basis for a statistical analysis [204] of consumer behaviour enriching standard user profile. Furthermore, this system permits to know customer's movements and visiting time to determine important aspects such as: most visited areas, average of time visiting, potentials of special offers. These considerations are needful for retailers to evaluate the performances of the point of sales and, eventually, to modify arrangement and communication strategies.

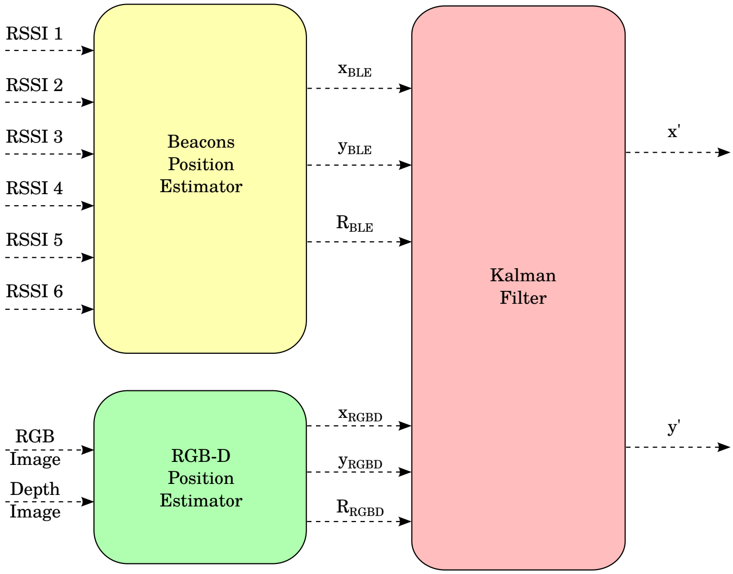

Figure 3.38: *"Kalman position estimator"*. *"Beacon position estimation"* and *"RGB-D position estimation"* fused together to obtain a more accurate localization of the BLE device.n.

Our positioning framework is defined in a real showroom. However, the method is general to be ported to other environments configuring location map and installing a number of active beacons sufficient to cover the area and obtain the requested accuracy. The room has a rectangular shape: $7.8m \times 15.0m$ with the ceiling at $4.0m$). It is important to remark the presence of an electromagnetic source of disturbance from electrical panel near the entrance and a window with steel studs on the left wall (see Figure 3.39).

We arranged a network of six beacons attached on the walls (at middle high of $2.0m$) and one RGB-D camera, with a top-view configuration, placed on the ceiling at the entrance (with a coverage area of $4.0m \times 3.0m$). The beacons are configured at maximum broadcast power of $+4dBm$ and ping frequency of $5Hz$. This configuration is not for battery saving but for to obtain a frequency capable to correctly track customers movements. The RGB-D camera is connected with the server by Wireless LAN. The testing application is developed using Estimote SDK with Xcode 7.0 and installed on an iPhone 4s running iOS 9.0. We intentionally partitioned the space with a rectangular grid of $3.9m \times 5.0m$, used as area of interest in clustering analysis (see Subsection 3.4.1.3). In the following we reported experimental results conducted to evaluate beacons performances for localization purposes and used in conjunction of the RGB-D sensors system, to verify increased accuracy in position

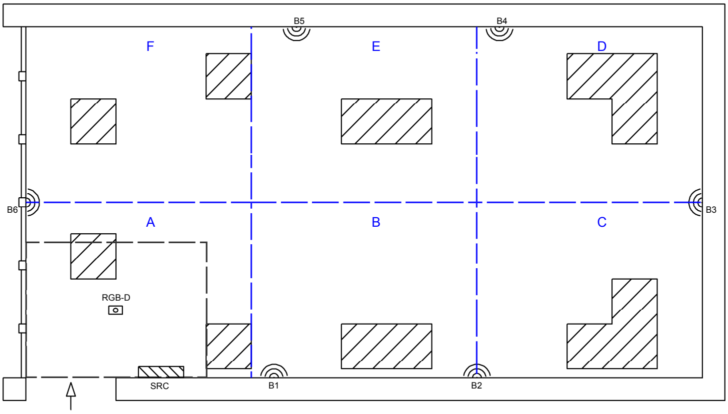

Figure 3.39: Showroom floor plan with positioning framework. Beacons (B1-B6), RGB-D camera (RGB-D) with coverage area (grey dashed rectangle), electrical panel (SRC labelled hashed block), furniture (hashed blocks), area of interest grid (blue dashed lines).

estimation.

To assess the reliability of the used localization technology into the real environment we performed preliminary tests, one to evaluate performances with different distances and one to observe the positioning behaviour over time. For the first test we fixed the smartphone over a rod at a height of $2.0m$ (the same of installed beacon), we traced the middle line of the room from position `B3` to `B6` and put a marker on the floor every $0.5m$ (from a distance of $0.5m$ from `B3` to a distance of $15.0m$ corresponding to position `B6`). We placed the device on each marker collecting beacon's broadcasting ping (from beacon positioned in `B3`) for each position at growing distances, considered from `B3`, starting from $0.5m$ to $15.0m$. With our testing application we collected a dataset of RSSI values, in order to have 60 samples ("Filtered samples") for each marker, with a maximum error-gap distance of $\pm 1m$. Error-gap is calculated as the difference between the "real distance" (the marker distance from `B3` measured with digital laser distance meter) and the "estimated distance" (the device distance from `B3` estimated with logarithmic signal attenuation curve provided by Estimote SDK). The nearest samples, acquired on markers with a distance below 3 meters, present an "estimated distance" very close to the real distance, in terms of error-gap, with low variance as shown in Figure 3.40. BLE radio signal, due to its frequency range and strength, is attenuated and reflected from the room (e.g., walls, floor, ceiling) and from objects inside it. This effect is evident when we are outside the beacon's proximity range, markers with a distance above 3 meters, and is more clear above 10 meters with a not

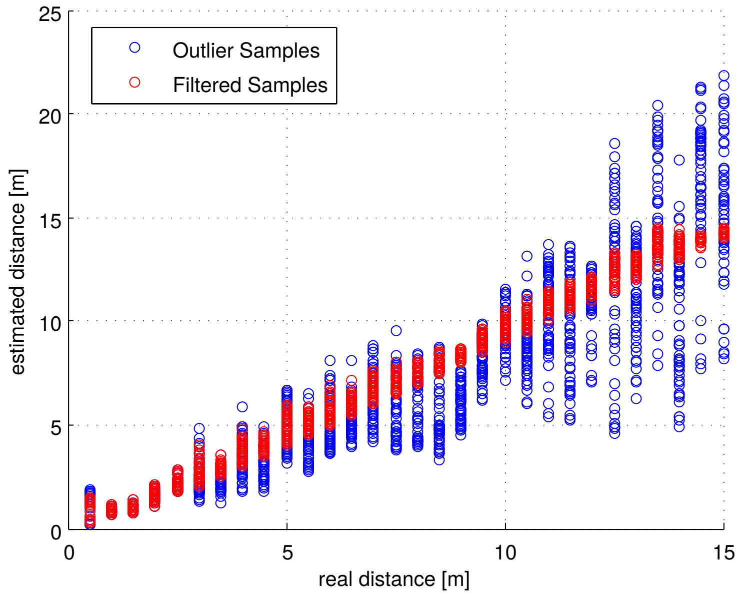

Figure 3.40: Estimated distance comparison for different real distances. Filtered samples are reported as red circles and outlier samples as blue circles.

acceptable accuracy decay.

Analysing RSSI values of “Filtered samples”, we obtained the correspondence between RSSI and distance in our environment. The result in Figure 3.41 shows that the trend is near the expected logarithmic signal attenuation curve. This is the curve that we adopted in the *“Beacons position estimation”*.

To observe the positioning behaviour over time we placed the same configuration (rod + smartphone at height of $2.0m$) in the centre of the room. With our testing application we collected a dataset of Beacons' raw data (broadcast ping from 6 beacons with power of $+4dBm$), for a total amount of 300 samples (with frequency of $5Hz$, a sample every $200ms$), estimating the device position with *“Beacons position estimation”* as relative coordinates. We repeated the same experiment switching the broadcasting power to $0dBm$ and then to $-4dBm$. Results of these three experiments are shown in Figure 3.42 as mean square error.

The positioning framework, tested only with beacons, has a delay to reach real position value. We registered a similar or longer “localization start-up time” decreasing broadcasting power. The effect of the electromagnetic disturbance source introduced an evident error in the estimation, that is higher with lower broadcasting power, not allowing a reliable localization. These tests demonstrated that active beacons are not self-sufficient to reach an indoor lo-

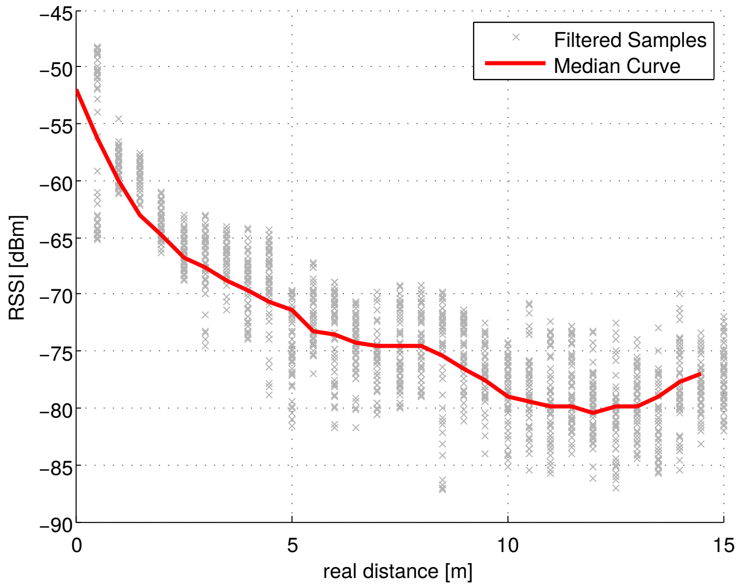

Figure 3.41: RSSI and distance relation. RSSI values of filtered samples are represented with gray crosses at their real distances. Median value is traced as red line.

calization able to provide tracking data for customers' analysis. For this reason in the next subsection we introduce our methodology, based on sensor fusion (Beacons + RGB-D camera), to overcome discussed issues.

Initially, to determine the best installation position for the RGB-D camera, we performed a test along a prefixed path with the already used configuration (rod + smartphone at height of $2.0m$). We put a series of markers on the floor progressively numbered starting from the entrance (see Figure 3.36 left) moving around the showroom like a horseshoe. In this way we positioned a total amount of 20 ground-truth points, with an inter-distance between $1.5m$ and $2.0m$. With our testing application running, we moved along the ground-truth path, collecting 30 samples for each marker, estimating the relative coordinates of the device with *"Beacons position estimation"*. Finally, we computed the mean square error of each position and results are presented as interpolated error-map (Figure 3.43). This error-map shows clearly the effects of the electromagnetic source of disturbance and the window with steel studs that mainly affect beacons in position `B6` and `B1`. In this way we detected the worst case area, choosing, within it, to install the RGB-D camera in the strategic position close to the entrance. The advantage is twofold: on the one hand to improve localization system by reducing the positioning error, on the other,

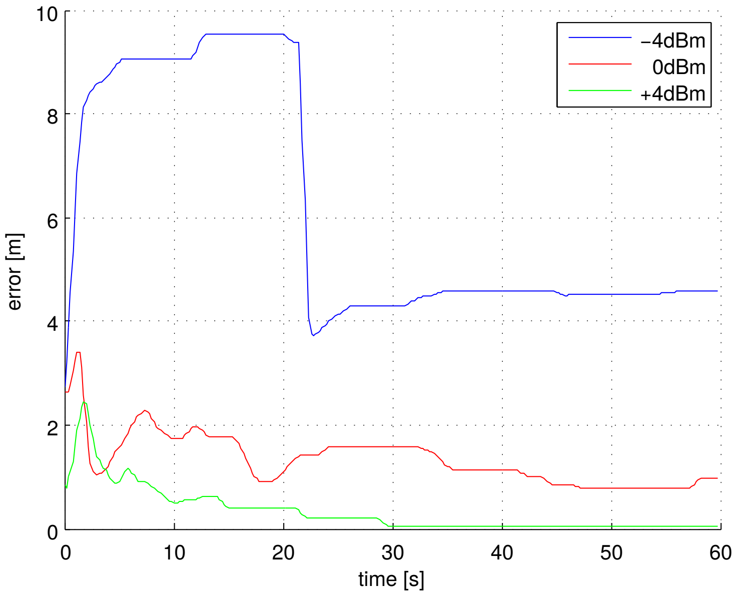

Figure 3.42: Estimation error over time for different broadcasting power.

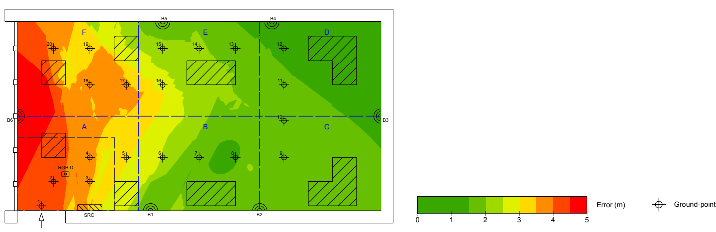

Figure 3.43: Error-map for "Beacons position estimation".

camera in that position can absolve different tasks (i.e., people counting and classification).

Data provided by *"Beacons position estimation"* and *"RGB-D position estimation"* are combined by a sensor fusion algorithm based on Extended Kalman Filter (EKF) (see Figure 3.38). The state vector of the model is expressed as follows:

$$\mathbf{x}_k = \begin{bmatrix} x_k & y_k & z_k & v_{xk} & v_{yk} & v_{zk} \end{bmatrix}^T \tag{3.1}$$

In the Extended Kalman Filter, the state transition and observation model don't need to be a linear functions of the state but may be a differentiable functions instead. Let's define the dynamic equation and the measurement equation respectively as:

$$\tilde{\mathbf{x}}_{k+1} = f(\hat{\mathbf{x}}_k, \mathbf{u}_k, \mathbf{w}_k) \tag{3.2}$$

$$\tilde{\mathbf{y}}_{k+1} = h(\tilde{\mathbf{x}}_{k+1}, \mathbf{v}_{k+1}) \tag{3.3}$$

where $\tilde{x}_k$ and $\tilde{y}_k$ denote the approximated *a priori* state and observation while $\hat{x}_k$ the *a posteriori* state estimation at the previous step. The process function f can be expressed as a linear function:

$$\mathbf{x}_{k+1} = A\mathbf{x}_k + B\mathbf{u}_k + \mathbf{w}_k \tag{3.4}$$

Sensor measurements at time k are modelled in a Kalman Filter by the following equation (measurement model):

$$\mathbf{z}_k = H\mathbf{x}_k + \mathbf{v}_k \tag{3.5}$$

The pose estimation from Beacons RGB-D systems define the H matrix in the following way:

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{3.6}$$

The measurement vector is expressed in the following way:

$$z = \begin{bmatrix} x_{RGBD} & y_{RGBD} & x_{BLE} & y_{BLE} \end{bmatrix}^T$$

where x_{RGBD}, y_{RGBD} represent the position estimated with the RGB-D camera, and x_{BLE}, y_{BLE} the position estimation using the set of beacons.

By repeating the experiment, we estimated the relative coordinates of the device with *"Beacons position estimation"* and with *"Kalman position estimation"*. In the Figure 3.44 are shown the errors of positioning, computed with beacons' raw data and with fused data.

Samples' relative coordinates, falling into RGB-D camera coverage area, are estimated by *"Kalman position estimation"* with an average error ten times smaller than ones obtained with *"Beacons position estimation"*. The spatial distribution of the mean square error calculated for *"Kalman position estimation"* is outlined in Figure 3.45.

The evidence of benefits introduced by this approach, permit to get more reliable datasets and is the starting point to track consumer path inside the store, as discussed in the following.

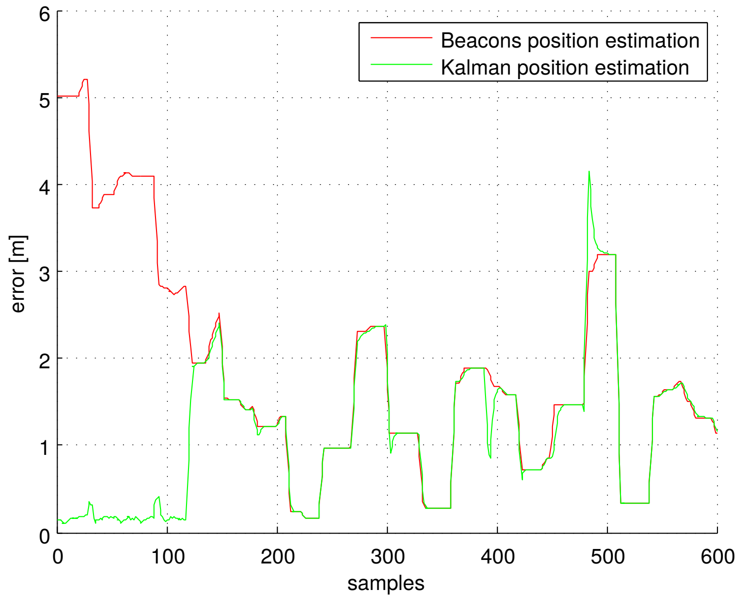

Figure 3.44: Comparison of mean square error between *“Beacons position estimation”* and *“Kalman position estimation”*. In *“Beacons position estimation”* the maximum error is $5.2m$, with an average error of $1.9 \pm 1.0m$. In *“Kalman position estimation”* the maximum error is $3.2m$, with an average error $1.0 \pm 0.7m$.

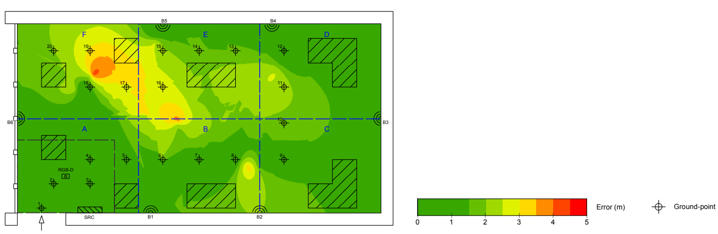

Figure 3.45: Error-map for *“Kalman position estimation”*.

3.4.1.3 Results

As final phase, we partitioned the showroom in six “areas of interest”, labelled from A to F as in Figure 3.39. The choice of grid size was driven by accuracy of position estimation reached with our positioning framework, as stated in Subsection 3.4.1.2. In each area there are expositors with products that should attract different kind of visitors (by range of ages). We marked the floor with the boundaries of these areas to be able to collect also the ground-truth area during the experiments.

Starting from a sample of 20 employers, male and female, we divided them by range of ages into three classes: 20–34, 35–49 and 50–65 (see Table 3.5). Every subject was provided with the smartphone and accounted on the testing application to couple the path with the person and his own profile. With our testing application running the subject was invited to move freely among the exposition spaces, registering the *"Kalman position estimation"*, with a frequency of $5Hz$. In the meanwhile an operator with another device, synchronized with subject's smartphone, was manually recording "area of interest" in which the subject was moving, in order to get the ground-truth area.

Ground-points used in position estimation (Section 3.4.1.2) are labelled with "area of interest", based on their space position (e.g., ground-point no. 8 inside the area B was labelled as B). These 20 ground-points represented the sample instances of each area and are used to estimate the Maximum Likelihood, based on Euclidean distance. Over $13,000$ *"Kalman position estimation"*, of tracked subjects, were classified with the corresponding "area of interest". This method allowed to obtain an overall accuracy of 85.5% (against the value of 76.0 with *"Beacon position estimation"*), as detailed in Table 3.4.

Table 3.4: Confusion matrix of classified *"Kalman position estimation"* per "area of interest". For each ground-truth area in the rows, with $_r$, columns report percentage of classified area, with $_c$. Bold values in the main diagonal (e.g., 89.9% for B_r and B_c) represent percentage of correctly classified, while the others are misclassified. Symbol – indicates no misclassified points with the area reported in the corresponding column. First row, with $_b$, reported results of classified *"Beacon position estimation"* for area A where is installed the RGB-D camera.

	A_c	B_c	C_c	D_c	E_c	F_c
A_b	*(18.5%)*	*(27.3%)*	*(–)*	*(–)*	*(26.0%)*	*(28.2%)*
A_r	**75.5%**	13.2%	–	–	7.1%	4.2%
B_r	–	**89.9%**	–	–	10.1%	–
C_r	–	19.5%	**79.5%**	0.3%	0.7%	–
D_r	–	–	1.1%	**96.9%**	2.0%	–
E_r	–	5.4%	0.1%	14.9%	**74.4%**	5.2%
F_r	2.2%	0.1%	–	–	1.0%	**96.7%**

These results highlights the improvement in the area (A) where is installed the RGB-D camera (from 18.5% to 75.5%). There are "areas of interest" with values under overall accuracy: A suffers of high error in the area not covered by the camera, while C and E present many customer paths near the transition area.

Creation of a regular grid with adjacent areas, covering all the space, leads to criticism when the device moved from an area to another. In particular, points falling into the transition buffer between areas, can be classified into different "area of interest", showing in the movement path an apparent "returning-back" or "chattering" effect, although the subject was moving straight to the other area. To correctly reconstruct the subject paths, we introduced a temporal filter, ignoring passages lasting less then $1sec$ (with sampling frequency of $5Hz$ means a minimum of 5 consecutive points in the same area). Applying this filter brings to a sequence of "area of interest" with a permanence time, representing each subject track, analysed in the next section.

Experimental tests demonstrate that our positioning framework, based on sensor fusion, allows consumer path tracking, providing useful input information to perform automatic costumer behaviour analysis.

At a first stage, we analysed all customers tracks, calculating a posteriori probabilities for people presence in an "area of interest" and for transitions between adjacent areas (see Figure 3.46). These probabilities can be used

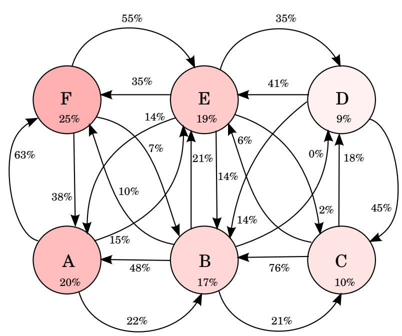

Figure 3.46: Markov chain with a posteriori probabilities. Nodes represent "area of interest" with presence probability, darker colours indicated high probabilities. Links represent passages between adjacent areas with transition probability. For example, node F has the higher presence probability of 25%, while link $C \rightarrow B$ has the higher transition probability of 76%.

to analyse movement trends inside the shop and comparing them with a priori expected behaviour, they can provide insights to improve product displacement and store layout.

Then, we computed, for all subject tracks, a map of the areas with a longer permanence time, greater than 4 seconds (see Figure 3.47). Although this heat-map highlights most visited area by permanence time, it's not able to distinguish which kind of subject, and then which cluster of potential shoppers [205], is interacting with the environment.

That said, we proceeded with a path clustering, to point out correspondences that should exist between recorded paths and range of ages. We reported results

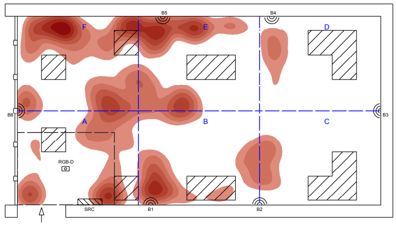

Figure 3.47: Heat-maps of paths. Darker colours represent visited areas with a longer permanence time (approximately 20 seconds).

of clustering, obtained with Expectation Maximization (EM) [206] method by cross validation, in Table 3.5.

Table 3.5: Path clustering results compared with range of ages. Bold values represent the correspondence between cluster and range of ages.

Age	Total	Cluster 1	Cluster 2	Cluster 3
20–34	7	**6**	0	1
35–49	7	1	0	**6**
50–65	6	1	**4**	1
Total	20	8	4	8

The final step here presented has the only purpose of proofing the concept of using tracking data for costumers behaviour classification. Even if the number of samples is not enough to evaluate the clustering method by itself, this approach show (Figure 3.48) the potentiality of identifying different customer behaviour and the suitability of the proposed methodology in an integrated data flow going from consumer tracking to consumer behaviour analysis and classification.

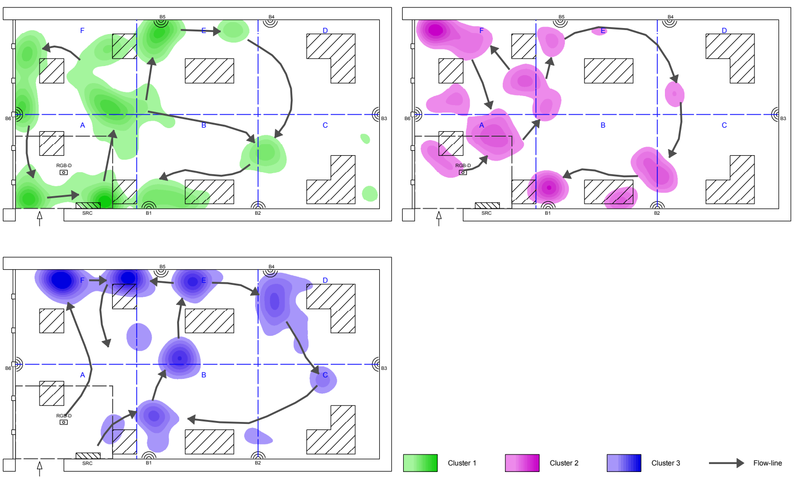

Figure 3.48: Heat-maps of paths computed by cluster. Darker colours represent a longer permanence time. Arrows are a schematic representation of flow analysis.

Chapter 4

Discussion. Limitations, challenges, lesson learnt

The examples illustrated and the use cases described so far, have proved that the new paradigm of *Senseable Spaces*, raised in the introductory Chapter, is able to solve both sides of the problem. The data collection from the space, along with the objects in it, has the twofold purpose of providing the users with contextual information which improve their knowledge of the space and to enrich the perception of the space itself. The increased knowledge of the users, that depends on the usage that they do about the services provided, opens up future scenario of improvement that are made not only with subjective analysis, but performed with an increased awareness, thanks to the data collected. Even if each scenario presents different features and needs, in every ambit it is possible to outline the dualism between the provisioning of data and the collection of data, regardless to the domain we are facing with. The different declination of *Senseable Spaces* experimented and showed, demonstrated that it is possible to cope with these needs. For the Cultural Heritage domain, broadly experienced for both museums and archaeology, emerged the need to set up fast and agile procedures allowing art curators to digitize their collections, present them in a digital form to the visitors, and to understand their insights. Thanks to the brief review (Chapter 1) of the work by the Senseable City Lab, we witnessed to a tremendous change in which it is possible to exploit the potentials of UGD for a better understanding of Public Open Spaces; tourists, or more in general citizens leave traces of their activities thanks to the use of their devices, while municipalities have the obligation to investigate these dynamics and provide planners with more efficient methods of urban design. Environmental changes are very difficult to be monitored; providing on site inspectors with suites of digital tools that ease the inspections, will facilitate the process and, moreover, will give the possibility to the decision makers to have more updated databases and GIS for a more constant monitoring and for a more aware policy making. Also the retail sector demonstrated to be a suitable domain to tackle; from one side, there is the need to engage customers with pervasive solutions, from the other to understand the performances of the space, of which the retailer is the owner, and plan, rearrange and redesign accordingly.

In table 4.1 a comprehensive comparison of the different actors, needs and points of contact are described.

4.1 Limitations

The common thread have been outlined; and it was also given an exhaustive description of the new possibilities offered by different technologies and approaches to provide and collect data. However, during our studies, emerged several limitations that still exist and that are preventing the spaces from becoming *Senseable Spaces*. In the case of Cultural Heritage for instance, emerged the necessity to present data in the more simple and usable way; this, to facilitate the fruition of cultural goods. The creation of 3D models is fundamental to know and visualize not existing buildings or artefacts that are not commonly visible to the wide public. We have seen how the integration and fusion of different data sources is the best solution, but it is worthwhile to underline the importance of the management of different LOD, since the same data could be exploited for visualization purposes (in different media like the WEB and mobile or with different interaction techniques) but also for restoration or reconstruction purposes, depending on the actor we are providing these acquisitions. The management of different LOD and the portability to different platforms needs further investigations.

An ample discussion was given, in Chapter 2, about the use of AR for different purposes (mainly CH, tourism and archaeology). With this study, we provide an exploration of research and application examples of different forms of AR. The taxonomy provided in section 2.3 demonstrates that this technology is suitable to be exploited for a large variety of sub-areas. What mainly emerges is the needs by the insiders to provide visitors with new hints about their collections. Whether museums can increase their attractiveness augmenting their artefacts or paintings with digital media, archaeological areas can bring to life lost architectures or ruins. For tourism, in the last years we witnessed to a tremendous use by the user of geolocation services to facilitate their exploitation of a space. Up to now, the most widely adopted application are those based on maps or web information. This survey is a showcase of how AR can be a supplement to this established trend. And more, diagnosis and restoration can be enhanced through similar solution. Not to mention the great potential of AR to improve the learning process. However, there are still many hurdles preventing AR acceptance and diffusion. Mainly due to: i) technological limitations, ii) content complexity and iii) human factors. Referring to *sensor-based* tracking, the main technical impediment is the error prone nature of built in sensor in commercially available devices. Up to now, the only solution is to improve hybrid techniques in order to overcome this limitation. Moreover, when people move in outdoor environments, every object can be a substantial source of information. This may cause a sense of confusion in the user who's searching for some specific areas or POIs, beyond the fact that the information content supporting location-based resource discovery is usually shallow. This issue is valid not only for the CH domain, but in any situation where the user is claimed at using this kind of services, like in the case of environmental monitoring. The response to this issue should be given by the use of ontology oriented services. One of the most important aspect to make AR spread to the wide public is the use of semantic web technologies. In this way, the user will have the possibility to enrich his/her own path and to personalize the visit according to his/her interests, or searching specific POIs based on a data layer, like the one proposed in Section 3.3, able to dictate the rules for a more comprehensive data management. This approach is not novel itself, since the approach can be found in literature from few years [92], [207]. The utilization of Semantic Web technologies, such as OWL, RDF, SPARQL was proposed to achieve the goal of enrich an existing AR browser in [208]. Author demonstrate that by querying an ontology based DB like Linked Open Data, the research of POIs can be tailored and facilitated at the same time. Similar example is showed in [209], where the main feature of the developed application is a semantic-enhanced POI search. For the CH domain, the most advanced project proposing a semantic approach in storing information about art is Europeana [1]. The introduction of semantics is necessary, since it also opens up to new possibilities in creating a participatory approach by the citizens [210].

Dealing with *vision-based* approach seems to be the most mature technology in terms of accuracy and reliability. Also in this case, the literature review shows a plethora of experimental application based on this method, though art curators and art managers do not endow AR solution as a must have in their exhibition. Mostly, the reason can be conducted to a lack of standardization which could facilitate a serial development. Some studies sustain that a service oriented approach could help in serialize the development of AR apps [211]. Others propose the standardization of a whole architecture for implementing AR apps [212]. From authors side, it is clear that while for geolocation AR the current standard is becoming widespread among the available frameworks, there is a lack for *vision-based* AR.

[1] http://www.europeana.eu/portal/en

4.2 Challenges

To create a more efficient interoperable *Senseable Space*, avoiding expensive errors, it is necessary to take into account the most popular standard yet in use for AR and AR-like applications (OpenGL ES, JSON, HTML5, KML, GML, CityGML,X3D, and so on). A real-time representation of 2D and 3D objects will be based on systems of projection of several types. By creating a standard data model, different for each domain, adding to the real world, a 3D model, together with multimedia objects (such as image, text, audio, video) and/or description, the community should benefit of self-documenting format that describes the structure as well as data types and meanings of values; simultaneously human and machine-readable format; representation of many data structures (lists, trees and records) and structures that can be addressed using standardized methods, such as XPath.
Technological limitations also include hardware capabilities for the display of complex 3D models; they are often huge and displaying of multifaceted items represents a hard task. In fact, computational capabilities cannot be managed in advance; since a real time rendering requires good hardware performances, planning applications for a wider range of user means finding a balance between complexity and efficiency. Internet availability is another obstacle, especially for outdoor settings. If the application needs to retrieve remotely stored contents, the user needs to rely on his own Internet provider. On the one hand, not covered areas prevent the use of the application, on the other limited bandwidth could make difficult loading files. All these aspects can be addressed and partially solved working on contents complexity. Referring to 3D models, they carry several features such as polygons number, file format, file size; at the same time, different platforms means different limitations. The problem is twofold: firstly, bigger files badly affect the possibility to quickly download them, secondly the more complex the model is, and the worst result is. Taking into consideration that subtle details cannot be seen, the best approach is differentiating the process depending on the purpose and the final result attended.

4.3 Lesson Learnt

The user experience deserve some comments. In fact, also human factors still prevent AR from become a daily used technology. It is generally a naive approach to wait for people stepping out of their comfort zones by their own choice; besides, using new technologies usually meet initial resistance. Mobile AR applications should be intuitive enough for users to learn and use independently, without the continued reliance on experts. Even if different approaches of interaction have been tested [213], the winning mix between model fidelity and app responsivity is the best solution to make the simple and enjoyable for users application. One of the most recent study about usability [214] confirms the above. This is a very important aspect, because the more services are usable, the more users are tempted to use them. The consequence of this will be a more productive data collection, that up to now represent another impediment. From the cases described in fact, the sampled activities are quite few, probably because the services provided were not understood as needful by the users.

During the experience of Mogliano festival (see section 3.2.1.4), active beacons were used with the double end of sending notification to the visitors entering a specific attraction and collecting their statistics (i.e. numbers of visits and visiting times). This is mainly due to the difficulty of tracking people movement via GPS location. In fact, as described before, canopy effects and lacks of signal may interfere with a continuous and reliable tracking. However, the sample of tracked visitor is not so wide. This is because BLE technology is not such widespread to cover a significant number of users; up to now, collecting UGD from different sources (photos, GPS, BLE, digital footprints and so on) seems to be the most powerful approach since there is not an existing solution able to cover a such wide spectrum of users. Still, our analysis are meant to complement, not replace, traditional surveys and other means of data collection. The advantage with respect to the predigital age, is that the mechanisms of extracting information, clustering human movements and understanding dynamics can be entrusted on the provisioning of specific services to the individuals. It is also expected that the use of UGD and mobile data in general can raise privacy and ethical concerns related to collecting data without the individual's consent. Using our approaches, as described in each scenario, addresses this concerns since only the identifier of the phones are tracked, without any information about the user's identity. Moreover, BLE based networks are not accurate in terms of precision; the solution realized for retail settings cope with this problem, avoiding the issue of interference sources. Nevertheless, the solution was specifically designed to be installed in indoor scenario and, conversely, in outdoor settings the issue of an accurate tracking is still open and requires future steps forward from the research community.

Table 4.1: Summary of challenges, limitation and issues related to the creation of *Senseable Spaces* in the different domain described

Senseable Space	Users	Scenario	Technology	Data	Needs	Limitations
Cultural Heritage	Visitors Museums' Directors	Indoor Outdoor	AR SfM MVS TLS GIS Mobile EyeTracking WSN HCI	3D models Images Video Audio RawData Spatio-Temporal Data	Clarity Appealing Knowledge Tools Knowledge	Standards Size Visualization HBA
Public Open Spaces	Tourists Citizens Planners	Outdoor	AR GPS Beacons WSN Mobile DataVisualization GIS	Notification Images Text GeoSpatial and Spatio-temporal Data	WayFinding Contextual Awareness Dynamics Knowledge	Accuracy Ubiquitous Pervasivity
Natural Environment	Inspector Policy Makers	Outdoor	AR GIS MAPS GPS Mobile DataVisualization GIS SpatialDB	3D models Text GeoSpatial and SpatioTemporal Data	Clarity Visualization Tools Dynamics Knowledge	Accuracy Ubiquitous Pervasivity
Retail	Customer Retailer	Indoor	AR Beacons RGB-D Mobile DataVisualization Vision	Text Audio Images RawData Spatio-Temporal Data	Contextual Services Push Call to action Dynamics Knowledge	Privacy

Chapter 5

Conclusions and future works

In this thesis, the new paradigm of *Senseable Spaces* was outlined. Experiencing technological solutions in different domains, our studies were oriented towards understanding potentials and weakness points, from a multidisciplinary perspective. A *Senseable Space* can be defined as a space able to provide user with contextual services, to measure and analyse their dynamics, to react accordingly, in a seamless exchange of information. Chapter 1 portraits the current line of research for both Space Sensing and Geomatics; these domains proved to be complementary to one another, given the assumption that the branches of Geomatics cover all the scales of data collection, whilst Space Sensing gives the possibility to provide the services at the correct location, at the right time. The necessary software/hardware components for AR systems have been outlined in Chapter 2, where a specific focus for the CH panorama provides a useful overview about the state of art applications for different sub-domains. This focus was chosen since AR embody the concept of augmentation and demonstrated to be a good tool for both outdoor and indoor settings. We can also summarize the entire work presented in these pages with the following question: are we able to design a space, regardless form the domain, capable to perform the bidirectional exchange of data between the space and the user? To fulfil this objective, use cases and experimental set-up where widely described in Chapter 3. The purpose of each scenario was to demonstrate the possibility to apply the concept of a *Senseable Space* in several domains; it was also the opportunity to outline points of contact among disciplines apparently different, but that can be joined thank to this common thread. In fact, as stated in Chapter 4, given the large number of case studies experiences, it was possible to outline needs, bottlenecks and weakness points for each domain.

5.1 Thesis contributions

The main contribution of this thesis can be summarized in the following aspects: first of all, the new paradigm of *Senseable Spaces* was applied in different research settings, verifying for each one the real feasibility. The innovation introduced by the present study is demonstrated by several scientific publications in the domains described. We proved, by developing innovative mobile applications, that AR can be experienced in front of a painting [50] as well as in large archaeological settings [71]; complex contents have been developed in order to make them suitable for different output, experiencing data fusion techniques to achieve relevant output suitable for different platforms [85]. Notwithstanding, monitoring user behaviour remain the best practice to be used in order to improve the services to the users. The example of using eye tracking technology as a data enrichment for AR application is a clear demonstration [148]. As well, POS today are not fully exploited as a collector of information. The experiences developed demonstrate that we are able, thanks to the use of pervasive solutions like sensors or beacons, to address the problem. The pilot project set up during the Mogliano Festival [215] demonstrates how is possible to collect UGD and provide users with transportation data in real time. And with different needs and purposes, indoor spaces can be designed and re-designed accordingly. The development of the novel indoor localization system, in a experimental setup achieved with the combination of radio beacons and RGB-D camera [216], allowed to achieve the objective of tracking customers' movements (and clustering them with a Markov Chain model), analysing the performances of a space and to providing contextual information. And more, a standardization of data, arising from GIS, processed to be used in AR for environmental inspection [35] was validated in real scenario, demonstrating the huge potential offered by a *Senseable Space* to be measured by providing users with multimedia solutions and applications.

Now, at the end of this dissertation, is more clear what is needed to make a space *Senseable*: the space, the technology, the users. Every solution described had, at the center of the experimentation, the end user, in different meanings: sometimes a visitor, sometimes a customer, sometimes a citizen. And from the results section of each scenario also emerged that, if we were able to reach the objectives of providing services and to collect data from the user, what is still missing to this chain to be accomplished is the ability to react to these information.

Future works will be steered toward these directions.

5.2 Future works

The work described in this document paves the way for future research. The outlook that is predictable for our cities is that we will live in always more connected spaces, where all the users (e.g. visitors of a museum, customers of a mall, tourists) will be induced to leave their digital traces (or footprints) to interact with their surroundings; the consequence is that anybody could use data to visualize, explore and learn more about them. In this scenario, the use of geomatics applications will be oriented on both data collection (to provide contents) and space sensing, in order to measure specific dynamics of a space. The extraction of knowledge from humans activities will be also facilitated by the increased availability of devices enabled to sense the environment. If we are currently thinking to the UGD as geolocated pictures that are shared in social platforms, it is plausible to think that in the future data will be more complex, for instance with the introduction of the third dimension in commercially available devices. This, could open up to new trends of collaborative *Senseable Spaces* where, meshing-up all these data, could enhance our knowledge, improve new forms of predictive maintenance, delineate new paradigms of cartography and so on. New forms of rapid and agile survey would be also a new opportunity for the CH panorama, to cope with the lack of diffusion of our heritage. This could lead to a great improvement on the digitization of countless goods, that could be made available to rest of the world.

As sole AR is not able to address the problem of CH diffusion, the need of AmI into museums environments, claimed in Chapter 2, will be one of the research topic that is worthwhile to tackle. Moreover, in the case of POS, we could be able to understand how (and if) it will be possible to influence human movements changing the contextual information according to these dynamics.

Scenarios where the users are the active part of the system, measuring and being measured at the same time. As stated by Carlo Ratti, “we can analyze the pulse of the city, moment to moment. Over the past decade, digital technologies have begun to blanket our cities, forming the backbone of a large, intelligent infrastructure; it becomes an ideal lab to study the link between technology and city planning”.

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