ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DOTTORATO IN ELETTRONICA, INFORMATICA E DELLE TELECOMUNICAZIONI

Smart Sensors For Interoperable Smart Environment

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PHD. THESIS
January, 2007 – December, 2009

DOTTORATO IN ELETTRONICA, INFORMATICA E DELLE TELECOMUNICAZIONI

CYCLE XXII – ING-INF/05

Keywords

Smart Environment

Smart Object

Human-Machine Interaction

Interoperability

Sensors

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Glossary

ADC	Analog-Digital Converter
DR	Dead Reckoning
DRU	Dead Reckoning Unit
HCI	Human-Computer Interaction
INS	Inertial Tracking System
EMF	Earth's Magnetic Field
EMI	Electromagnetic Interference
KP	Knowledge Processor
LBS	Location Based Services
LUT	Look-Up-Table
MR	Magneto Resistive
MSB	Multi -Sensor –Board
OIP	Open Innovation Platform
PS&Com	Power Supply and Communication
PNS	Pedestrian Navigation System
PTU	Pedestrian Tracking Unit
SE	Smart Environment
SIB	Semantic Information Broker
SO	Smart Object
SOPM	Smart Object Power Manager
SS	Smart Space

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Abstract

Smart Environments are currently considered a key factor to connect the physical world with the information world. A Smart Environment can be defined as the combination of a physical environment, an infrastructure for data management (called Smart Space), a collection of embedded systems gathering heterogeneous data from the environment and a connectivity solution to convey these data to the Smart Space.

With this vision, any application which takes advantages from the environment could be devised, without the need to directly access to it, since all information are stored in the Smart Space in a interoperable format.

Moreover, according to this vision, for each entity populating the physical environment, i.e. *users*, *objects*, *devices*, *environments*, the following questions can be arise: "*Who*?", i.e. which are the entities that should be identified? "*Where*?" i.e. where are such entities located in physical space? and "*What*?" i.e. which attributes and properties of the entities should be stored in the Smart Space in *machine understandable* format, in the sense that its *meaning* has to be explicitly defined and all the data should be *linked together* in order to be automatically retrieved by interoperable applications.

Starting from this the location detection is a necessary step in the creation of Smart Environments. If the addressed entity is a *user* and the environment a *generic environment*, a meaningful way to assign the position, is through a *Pedestrian Tracking System.* In this work two solution for these type of system are proposed and compared. One of the two solution has been studied and developed in all its aspects during the doctoral period.

The work also investigates the problem to create and manage the Smart Environment. The proposed solution is to create, by means of natural interactions, links between objects and between objects and their environment, through the use of specific devices, *i.e. Smart Objects*

Chapter 1

INTRODUCTION

"*The traditional computer is a glass box. All you can do is press buttons and see the effects. Ubiquitous computing and augmented reality systems break this glass box linking the real world with the electronics worlds.*". These are words of Alan Dix, deriving from his book Human-Computer Interaction (Dix, 2004). In this book, Dix shows how computer has broken out of its plastic and glass bounds providing us with networked societies where personal computing devices from mobile phones to smart cards fill our pockets and electronic devices surround us at home and work. As the distinctions between the physical and the digital, and between work and leisure start to break down, Human-Computer interaction is also changing radically.

As Dix suggests, the way on which we are moving from an "Information Society" to a "Knowledge Society" involves research regarding various sectors. To summarize this migration a word has been introduced: Ubiquitous Computing. This term was born with the visionary work of Mark Weiser in mind (Weiser, 1991) (Weiser, 1996):

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

Consider a scenario like this: it's night and you are awake. So you get up and go in the kitchen. Then you open the freezer and catch the chocolate ice cream box. "No" says the fridge, "it's the two o'clock in the morning and you have the cholesterol level high". This scenario has shades of *Minority Report*, the Steven Spielberg movie based upon the great futurist Philip K. Dick's short story by that name. In fact, in the film, when the hero, John Anderton flees from the authorities, he passes through the crowded shopping malls. The advertising signs recognize him by name, tempting him with offers of clothes and special sale prices just for him. *Minority Report* was a fiction but the technology depicted in that movie was designed considering the Ubiquitous Computing idea. For example advertising sign are already close to becoming a reality. Billboards in multiple cities recognize owners of Mini Cooper automobile by the RFID tags they carry. This is only an example and a lot of work must be done to arrive at the *Minority Report* scenario.

This jump in science fiction introduces the concept of technology "*Any time, anywhere, any device*". This concept means the transition from a device-centered world to a new type of interconnected society, where information is spread around the environment and a large set of different technologies and devices are used at the same time with seamless transition of information from one to another.

1.1 Scenario

As mentioned, the Ubiquitous Computing is about research regarding various sectors. In fact, the above mentioned *Any time, anywhere, any device* technology can be seen as the interaction between physical environment, people, sensors, devices (Fig. 1. 1).

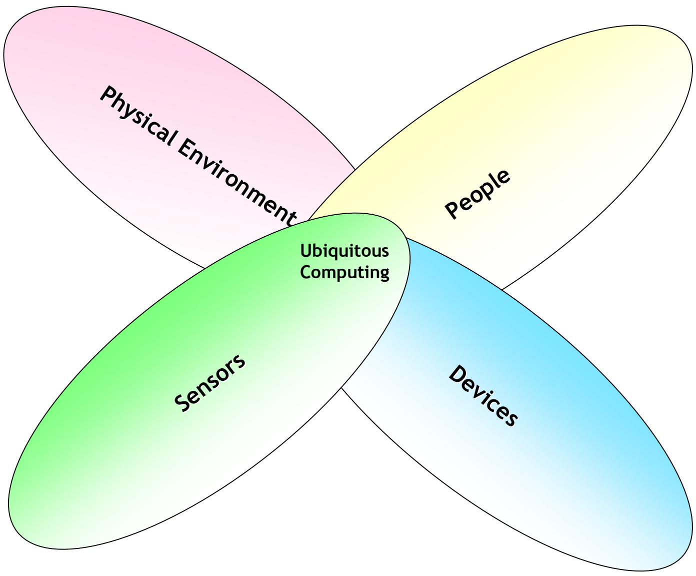


Fig. 1. 1 Ubiquitous computing interactions

The physical environment surrounds people which live in it. People wear or carry mobile devices. Physical environment is composed by objects which can be equipped of sensors. Sensors can be installed in the physical environment.

One of the visions of the Ubiquitous Computing is from the environment point of view. The research field in which the principles and the methodology necessary to the creation of intelligent environment are studied, is called *ambient computing*. Starting from physical environment, the *ambient computing* allows to create environments in which heterogeneous devices interact with each other, with people and with the physical environment itself, allowing the identification of contextual relevant services and adapting them to the situation and to the user profile and preferences. These type of environments are called Smart Environments (SE) (Fig. 1. 2).

Fig. 1. 2 Smart Environments

A Smart Environment is a world where "*all kinds of smart devices are continuously working to make users' lives more comfortable*" (Cook, 2005). Smart Environments aim to satisfy the experience of individuals from every environment, by replacing the hazardous work, physical labor, and repetitive tasks with automated agents. Another definition of Smart Environments derives from Mark Weiser: "*a physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, embedded seamlessly in the everyday objects of our lives, and connected through a continuous network*".

In Smart Environment the context of the occupants is detected. In this way contextual information can be used to support and enhance the ability to execute application specific actions by providing information and services tailored to user's immediate needs (Ryan, 2005). The smart devices which work together are interconnected with each other. These smart devices has to provide contextual information. For this reason they have to be equipped by sensors which provide low level data. If the contextual information is the users' one, the smart devices are mobile devices carried from the user. Devices that are able to connect people and environment within the Smart Environment are called Smart Objects (SO).

A Smart Environment can be defined as the combination of a physical environment, an infrastructure for data management (called Smart Space SS), a collection of embedded systems gathering heterogeneous data from the environment and a connectivity solution to convey these data to the Smart Space (Fig. 1. 3).

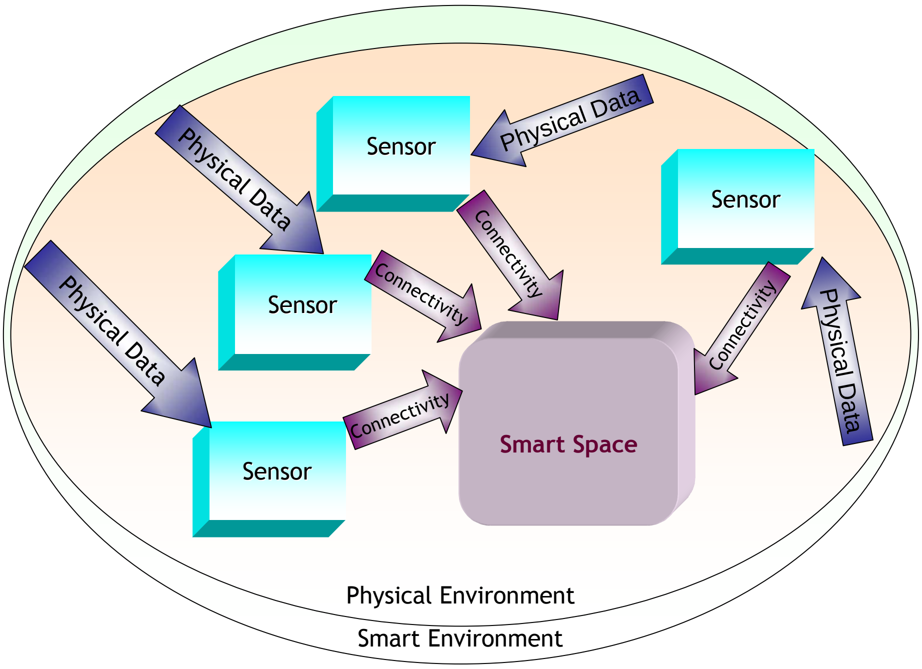


Fig. 1. 3 Smart Environment Components

To realize Smart Environments numerous amount of technical challenges must be overcome. The technical challenges may be summarized as how to create a consistent architecture for a Smart Environment characterized by three equally important trends: Multi-Part, Multi-Device, and Multi-Vendor interoperability (*MMM interoperability*), dynamic device configurations and extreme scalability.

Interoperability is defined from IEEE (IEEE, 1990) as the ability of two or more systems or components to exchange information and to use the information that has been exchanged. A more accurate definition is: Interoperability is the capability of a product or system to interact and function with other products or systems, without any access or implementation restrictions.

The interoperability is the requirement to provide to the users seamless connectivity and seamless services supplying (Salmon, 2008):

- platform interoperability: same services run on different platforms, *e.g.* devices, Smart Phones;
- data interoperability: services work on a common representation of data, and are independent from their data sources;
- network interoperability: the connection takes place to the best available network.

Focusing on interoperability, the aim of a Smart Environment is to provide *cross-domain interoperability* and *cross-industry interoperability*. The *cross-domain interoperability* is about the interconnection and communication between different technological platforms, possibly developed within different application domains. The *cross-industry interoperability* deals with technical interoperability issues, such as commercial strategies, licenses, and regulations. This type of interoperability can be called Multi-Part, Multi-Device, and Multi-Vendor interoperability (*MMM interoperability*).

The Smart Environment problem could be decomposed in several problems, each of them open research issues:

- the context-aware computing problem
- the mobile computing problem
- the problem of creating and interfacing context providing sensors
- the problem of creating usable and friendly interfaces between devices and people.

1.1.1 Context Aware Computing

People have always used the context of the situation to get things done. We use our understanding of current circumstances to structure activities, to navigate the world around us, to organize information, and to adapt to external conditions. Context awareness has become a integral part of computing. Context awareness computing aims to adapt the service to the current situation. To provide the fittest service, the system has to observe the inhabitant and the environment to collect information. The context is "*all information which can be used to characterize an entity. any information that can be used to characterize the situation of an entity. An entity is a person, place ,or object that is considered relevant to the interaction between a user and an application, including the user and application themselves*" (Dey, 2001). This broad definition allows to define in every scenario the most suitable specialized definition of context, which is needed for every practical implementation of Context awareness.

Several different definition are proposed in literature. A survey of the most relevant current approaches to modeling context for Ubiquitous Computing is proposed in (Strang, 2004). A review of the context-aware systems from 2000 to 2007 is proposed in (Hong, 2009).

(Schilit, 1994) refers to context as location, identities of nearby people and objects and changes to those objects. Also (Brown, 1997a) defines context as location, identities of the people around the user, the time of day, season, temperature, etc.

(Coutaz, 2005) points out that context is not merely a collection of elements (a state) but it is a part of the entire Human-Computer Interaction (HCI discussed further on) process or interaction within an ever-changing environment, made by a set of entities, a set of roles (of entities) and relations (between entities) and a set of situation.

The requirements for an infrastructure that supports Context Aware application are (Dey, 1999):

- To allow applications to access context information from distributed machines in the same way they access user input information from the local machine;
- To support execution on different platforms and the use of different programming languages;
- To support for the interpretation of context information;
- To support for the aggregation of context information;
- To support independence and persistence of context widgets;
- To support the storing of context history.

1.1.2 Mobile Computing

Today's trends see the introduction of a new figure of users: the *nomadic* user. In the context of Smart Environments, the trend in this case introduces high-capabilities devices spread in the environment and mobile devices, wearable devices and in general high computational capacity computers which move together with the user. As a consequence, the devices need increased capabilities. Internet-capable smart cell phones, wireless-enabled PDAs, tiny mobile devices which utilize last generation CPUs, high storage memories, several communication capabilities, has been introduced. In this case the cooperation between the user and the Smart Environment is explicit, in that the user has to interact with the mobile device to perform a task.

If the mobile device is worn from the user, if it is created for a specific task, or if the cooperation from the user and the Smart Environment is implicit, the mobile computing flows into the field of wearable computing. The aims of wearable computing is to connect the user to an adaptive personal intelligent environment. Research on tiny embedded devices, small sensors, high capacity in situation adapting, affect this implicit cooperation between users and Smart Environment.

If we define Smart Objects as devices that are able to connect people and the Smart Environment, it is easy to see that all the issues considered in the creation of mobile devices and wearable devices have to be taken into consideration also in the case of Smart Objects.

1.1.3 Context providing Sensors

Sensors are the link between digital and physical world. In fact, the automatic context acquisition is a prerequisite in order to capture real world situations. This phase is characterized by the usage of a multitude of sensors. Sensors are used to capture the characteristics of the physical world. As seen in (Goertz, 2004): "*A sensor is a device that perceives a physical property and transmits the result to a measurement. A sensor maps the value of some environmental attribute to a quantitative measurement.*" Then sensors provide the *intelligence* to the physical environment.

The conceptual flow from physical data to extracting contextual data is exposed in Fig. 1. 4: physical data are spread in the world; Smart Environment contains sensors; data are captured from the sensors; the combination and fusion of multiple sensor output can be used; the transformation of this data into relevant contextual data requires the knowledge of the situation in which these data has to be utilized. The problem of sensor fusion is particularly important in the extraction of contextual data: a sensor might not produce sufficient information due to uncertainty and unreliability of the sensor itself. Two types of sensor fusion are present: the competitive and the complementary. The competitive sensor fusion is based on sensors which detect equivalent physical data, trying to diminish the errors in the measurements of every sensor. The complementary sensor fusion utilize different typologies of sensors to extract high level data.

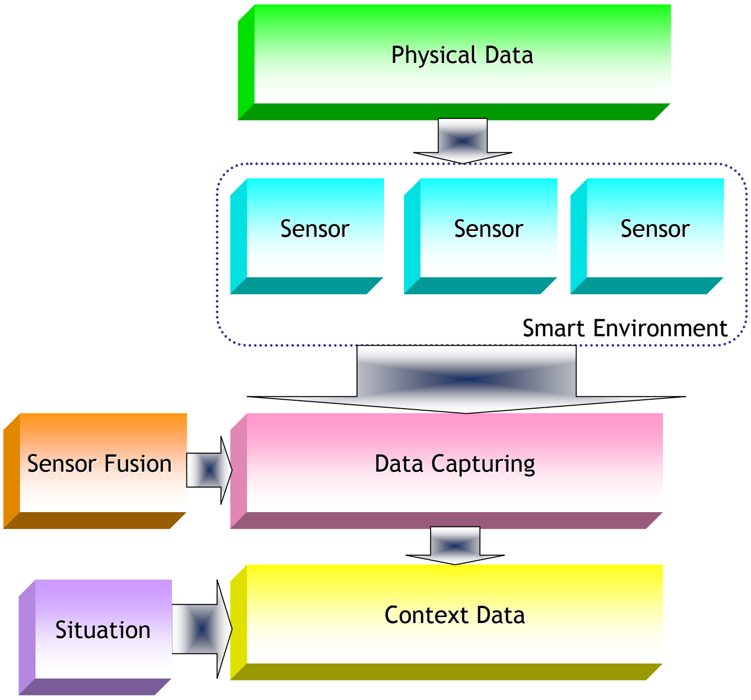


Fig. 1. 4 From Physical to Context Data

1.1.4 Human-Machine Interfaces

"But lo! men have become the tools of their tools" (Thoreau, 1854).

Although this sentence derives from an old and non-related book, it summarizes very well the problem of the interaction between human and machine. As mentioned by Donald Norman in his work *The Design of future things* (Norman, 2007), the relevant problem of interaction between human and machine occurs because we are two different species which work, think and act in different manner and utilizing different mechanisms. Devices are "stupid" and the management is always a major problem of the user because human have greater adaptation capabilities. Then, the entire research and commercial community is trying to solve the problem called Human-Computer Interaction (HCI). When considering Smart Environments, the problem of interaction as a support of the communication from the Smart Environment and the user is a crucial point. The goals of interaction are: supporting adaptative interfaces of devices on user's preferences, supporting self-configuration of devices to collection of interaction devices, providing a loop for interaction with the environment and feedback loops for information gathering from the environment. Interaction in the context of Smart Environments can be either active (explicit) interaction or passive (implicit) interaction by means of ambient sensors and contextual data tracking. In every cases the successful of the interaction between human and machine trying to avoid the lack of common ground. "*The lack of common ground precludes many conversation-like interactions*" (Norman, 2007), freezing the communication channel form people to devices.

1.2 Research Framework

This research work fits within the above mentioned Smart Environment problem. In this Paragraph the context of this research is shown and the correlation between the different parts are explained.

Smart Environments are currently considered a key factor to connect the physical world with the information world. As seen, a Smart Environment can be defined as the combination of a physical environment, an infrastructure for data management (called Smart Space), a collection of embedded systems gathering heterogeneous data from the environment and a connectivity solution to convey these data to the Smart Space. With this vision, any application which takes advantages from the environment could be devised, without the need to directly access it, since all information are stored in the Smart Space in a interoperable format. Moreover, according to this vision, for each entity populating the physical environment, i.e. *users, objects, devices, environment part*, the following questions can arise:

- "*Who*?", *i.e.* which are the entities that should be identified*?* Each single element of a physical space should be *identified*. It is accepted from the research community that the RFID technology will play a primary role with respect to this. "*It is foreseeable that any object will have a unique way of identification in the coming future, what is commonly known in the networking field of computer sciences as Unique Address, i.e. already today many RFID tags operate with a 128 bits address field that allows more than a trillion unique addresses for every square centimetres on the earth, creating an addressable continuum of computers, sensors, actuators, mobile phones; i.e. any thing or object around us*." (EPOSS, 2008). This is the concepts of the Internet of Things. Research community open questions are mainly related to security, privacy, standardization and power consumption. "*Another central issue of the Internet of Things will be related to trust, privacy and security, not only for what concerns the technological aspects, but also for the education of the people at large…Obviously, all such devices will need to harvest their own energy. Overcoming the power* *problem will allow the things not only to communicate for indefinitely long, but also to relay information from other objects.*" (EPOSS, 2008). Research are also investigating on how to identify, search for and locate RFID tags spread across the environment by combining for example vision techniques and augmented reality (Kunkel, 2009). In fact, one of the main limit of this technology concerns the limited range of detection, mainly for passive RFID tags. Moving to high frequency and powered tags, i.e. 2.45 GHz active tags, will open new research challenges to find the best trade-off on power consumption, distance range and accuracy.

- "*What*?" *i.e.* which attributes and properties of the entities should be stored in the Smart Space in machine-understandable format, in the sense that its meaning has to be explicitly defined and all the data should be linked together in order to be automatically retrieved by interoperable applications. Functional to reach this goal is the use of ontologies. They represent logical instruments defining class hierarchies and properties, *i.e.* the domain and the range.
- "*Where*?" *i.e.* where are such entities located in physical space? Elements within the physical space should also be *located.* A lot of research have been carried out in past years aiming to find solutions for tracking the position of people, vehicles and objects. In outdoor open sky environments, the GPS represents for sure the well know and adopted solution to track people and vehicles. In unconstrained environments, *i.e.* indoor-outdoor, the lack (or the weakness) of the GPS signal imposes to adopt other solutions, mainly based on the integration of different technologies, like for example Inertial Systems, Wi-Fi, Bluetooth, Zigbee, WiMax and RFID. In general, location granularity is closely related to the adopted space representation and to the application, *e.g.* an object is in a building, an object is in a room of the building, an object is on a table inside a building's room, an object is geo-located with respect to a coordinate reference system. Representing spatial data raises the same problem of giving a common *meaning* to such data.

The above questions implies a necessity: the Smart Environment has to be location-aware, in the sense that it must be able to know the position of mobile entities (*users, objects* and *devices*) at any time. This contextual data is the one taken into consideration in this research work considering human as entity. Then the research has been focused on *Pedestrian Positioning* systems which provide the position of a user which wears them. One of the requirements of these *Pedestrian Positioning* system is their integration in a Smart Space.

The existence of the Smart Environment is an hypothesis which has to be made in order to perform every Smart Environment application. For this reason the creation of the Smart Environment starting from an heterogeneous physical environment is the first step to take into consideration in every application. This creation has to be performed in the easiest, fastest and most natural manner. A innovative way to create Smart Environment starting from physical environment has been studied and considered in this research.

The object utilized to perform this task is critical. The design and development of a Smart Object aimed to supply this duty, has been taken into consideration during the PhD period. This Smart Object permits the user to create a Smart Environment starting from any physical environment in a easy way. Moreover, this Smart Object helps in the challenging task of managing the Smart Environment.

Fig. 1. 5 shows the overview of the research. The framework in which all the research is contained is the EU 7th Framework Programme SOFIA (*Smart Object for Intelligent Applications*) project, within the ARTEMIS Joint Technology Initiative. It has taken on the challenge of answering the following question: how can all these heterogeneous personal devices, sensors and Smart Objects interact with each other in order to provide meaningful and useful services when and where they are needed? SOFIA aims at "*making information in the physical world available for smart services, connecting physical world with information world*". Functional to this challenge is interoperability at different levels: *communication*, *service* and *information*. Interoperability should also reflect the *Multi-vendor* (*i.e.* the user shall be free in choosing the manufacturer), *Multi-device* (*i.e.* many kinds of devices shall interact with each other), and *Multi-part* (*i.e.* a device may be composed of parts that are considered as individual partners for interaction with another device), nature of the above envisioned scenario. New architectures and platforms will result from these research.

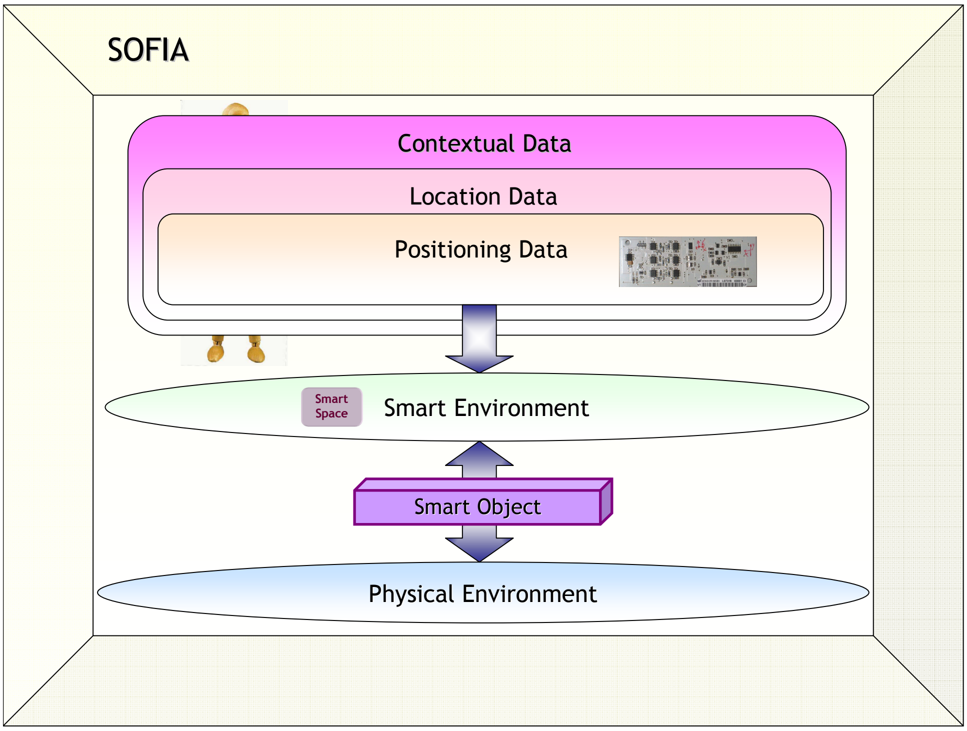


Fig. 1. 5 Research Framework

1.3 Thesis Outline

The thesis is organized as follows.

In Chapter 2, an overview of the problem concerning the Smart Environment creation and management is shown. In this chapter an introduction of Smart Environments definitions and background is provided, and some examples of the utilization of Smart Environment in the smart housing dominium are shown. The basis of a new vision of the concept of Smart Environment carried on in the project SOFIA, with its components and definitions, is shown and two applicative example of the use of the Smart Environment are exposed, one of this is taking into account the location problem.

Chapter 3 and Chapter 4 aim to provide an overview on interaction concepts that support user interaction techniques and user interaction metaphors in different Smart Environment situations and for different users regarding individual preferences and characteristics. In particular Chapter 3 introduces the concepts of Human-Computer interaction. Interaction paradigms are shown and the definition of Smart Object, an overview of the possible application in which it could be employed and the state of the art of the utilization of Smart Object as Interaction device are shown. Chapter 4 presents the design of a particular type of Smart Object which duty is to creation and managed Smart Environment starting from physical environment.

Part II is about the problem of making the Smart Environment location aware, taking into consideration the users positioning systems. In Chapter 5 an overview on Pedestrian Positioning Systems is presented, giving a justification to the work developed in the PhD period regarding the Navigation Systems, and making an excursus of the other works present in this research area. In Chapter 6 the project of the entire hardware and software platform is presented, which permit the estimation of static direction through a one axis gyroscope and a two axes accelerometer. The presence of a magnetic compass integrated in the system is investigated. In Chapter 7 the second approach to estimating the orientation of a pedestrian user is presented. This approach has been studied and developed in all its aspects, according to the Pedestrian Tracking System Requirement. The approach is based on a three-axes accelerometer and a two-axes magnetic sensor, whereby the user orientation in expressed as if he or she is wearing a compass. In Chapter 8 the analysis of a human walking is exposed. To detect the steps, the data derived from the Accelerometers have to be taken into account. Different algorithms, also depending on where sensors are worn, are performed. In this Chapter two different approaches for sensors wearing on belt are presented: the first one utilizes only the frontal acceleration and the second one utilizes the frontal and the vertical accelerations. In Chapter 9 the two approaches to estimate the users orientation and the two steps detection algorithms are compared and results on these are exposed.

Chapter 2

SMART ENVIRONMENTS

A Smart Environment is a world where all kinds of smart devices are continuously working to make users' lives more comfortable (Cook, 2005). The context of the occupants is detected. In this way contextual information can be used to support and enhance the ability to execute application specific actions by providing information and services tailored to user's immediate needs (Ryan, 2005). The smart devices which work together are interconnected with each other. These smart devices has to provide contextual information. For this reason they have to be equipped with sensors which provide low level data. If the contextual information is the users' one, the smart devices are mobile devices carried by the user.

The Smart Environment has to be location-aware, namely it must be able to know the position of mobile entities (people or devices) at any time. These contextual data are the ones taken into consideration in this PhD work, developing a Pedestrian Positioning system which provides the position of a user that wears it.

This Chapter shows an overview of the above mentioned problems, starting from an introduction of Smart Environments definitions and background in Paragraph 1. Some examples of the utilization of Smart Environment in the smart housing dominion will be shown. Paragraph 2 shows a new vision of Smart Environment carried on in the project SOFIA, with its components and definitions. Two applicative example of the use of the Smart Environment are also shown, one of this has taken into account the location problem. The solution of the creation of a Smart Environment problem is also considered. One of the requirements of this Pedestrian Positioning system is its integration in Smart Spaces. In this paragraph also this integration will be shown.

2.1 Smart Environments Background

The Smart Environments are based on platforms called Context Management Systems. These Context Management Systems contain relevant contextual information. The hearth of Context Management Systems is the Context Storage. An overview of existing Context Management Systems is shown in Paragraph 2.1.2.

The aim of a Smart Environment is to provide *cross-domain interoperability* and c*ross-industry interoperability*. The *cross-domain interoperability* takes care of the interconnection and communication between different technological platforms, possibly developed within different application domains. The *cross-industry interoperability* takes care of technical interoperability issues, such as commercial strategies, licenses, and regulations. This type of interoperability can be called Multi-Part, Multi-Device, and Multi-Vendor interoperability (*MMM interoperability*).

To enable the *MMM interoperability*, the information must be written in a machine readable method. In this way it is allowed the exchange of information without loss of meaning and among different applications running on different devices in any physical space. There are several manner to structure the data to represent and share contextual information:

- Key-value pairs: they are the simplest data structure to model data. They are easy to manage, but lack capabilities to enable efficient context retrieval algorithms;
- Markup scheme: it is a hierarchical data structure consisting of Markup tags with attribute and content. The most common Markup language is the eXtensible Markup Language (XML) (Bray, 2006);
- Graphical model: the most famous graphical model is the Unified Modelling Language (UML);
- Object-oriented model: this approach is easy to use due to its encapsulation and its reusability;
- Logic-based model: a logic defines the conditions on which a concluding expression or fact may be derived from a set of other expressions or facts. To describe these conditions, a set of rules are applied. Utilizing the logics it is possible to perform reasoning;
- Ontology-based model: the term *ontology* derives from philosophy. An ontology defines a common vocabulary for researchers who needs to share information in a domain. It includes machine-interpretable definitions of basic concepts in the domain and the relations among them. The representation of the knowledge is performed utilizing a model constituted of *classes* and *attributes* (or properties). The classes are the general models of the entities of the represented system. They describe concepts in the domain. The properties are the connections between the entities defined through the classes. Another definition of ontology is reported in (Gruber, 1993): a formalization of a conceptualization.

If the information are exchanged utilizing a common vocabulary, the applications based on this information become interoperable. In Paragraph 2.2.1 a developed example of on interoperable application utilizing an ontology data model is shown.

As seen, a Smart Environment is an ecosystem of interacting objects, *e.g.* sensors, devices, appliances and embedded systems in general, that have the capability to self-organize, to provide services and manipulate and publish complex data. In this heterogeneous dominion, the user interaction techniques and user interaction metaphor are particularly important. The creation of objects which support the interaction between human and Smart Environment, according to the Human-Computer Interaction metaphors, is particularly important. These objects are called Smart Objects. The development of a specific Smart Object which accomplishes the Natural Interaction Model is exposed in Chapter 4.

Some Smart Environment architectures are present in the research world, and several utilize ontologies to model the context. One of the most famous architecture is SETH (Marsa-Maestre, 2008). The SETH architecture proposes an agent-based software architecture for urban computing environments. One of the challenges of this architecture is to cope with the high number and diversity of available services. In SETH, a Smart Environment is composed by a set of devices, a set of available services and a given context.

A middleware based on Service-Oriented Architecture for context-awareness in a home network with ubiquitous computing is presented in (Kim, 2007). It suggests a context model supporting semantic level interoperability of context.

The CoBra system (Chen, 2004) is an architecture that provides runtime support for context-aware systems in ubiquitous computing environments. Central to CoBrA is a server agent called context broker. Its role is to maintain a consistent model of context that can be shared by all computing entities in the space and to enforce the user-defined policies for privacy protection.

(Dey, 1999) discusses the requirements for dealing with context in a Smart Environment and presents a software infrastructure solution designed and implemented to help application designers build intelligent services and applications more easily.

2.1.1 Context Managements Systems for Smart Environments

The Smart Environment are based on platform called Context Management Systems. These Context Management Systems contain relevant contextual information. The hearth of these is the Context Storage. Producer, Consumer and Aggregator are entity which accede to the Context Storage. A Producer acts as a context producer. Producers register their availability and capabilities by sending appropriate information to the Context Storage. Their purpose is to collect raw context data from sensors and other dynamic/static sources, including configuration files for device capabilities and user-preferences. Producers transform their input into context elements which are then put into the Context Store. A Consumer uses context data. A Consumer can receive notification of events from the Context Storage and it can perform some actions based on the event. On receiving a notification, the Consumer may get the element from the store and use it as required. An Aggregator combines the behaviour of both a Producer and a Consumer. Aggregators monitor events from the Context Storage, rather than a sensor device, and apply a transformation before returning a new element to the context store. Aggregators can combine several low-level sensor elements to produce an element at a higher level of abstraction. For example, temperature, door, window and light sensor information might be used to determine room occupancy. Other Aggregators may perform simple transformation services, *e.g.* converting latitude and longitude coordinates from a GPS sensor to coordinates on an appropriate local or national grid. An extensive description of infrastructure for context provisioning is exposed in (Baldauf, 2007).

The first example of support solution for context management is the Context Toolkit (Dey, 2000). The system is based on a centralized discovery server where distributed sensor units interpreters and aggregator are registered in order to be found by client applications.

The infrastructure presented in (Rey, 2004) is called Contextor and has a set of abstraction levels for context data and a computational model. The lowest abstraction level is the sensing layer, in which raw data values are assigned to observables. The other levels are: the transformation level (association of symbols to observables), the situation level (identify inference and reasoning to identify associations) and the exploitation level (adapt information from the infrastructure to the applications).

In (Gu, 2005) the SOCAM project is proposed. This middleware hepls a developer in the creation of context-aware services for mobile devices. Also the Hydrogen project (Hofer, 2003) has as its target the mobile devices. This architecture is based on three layers: the adaptor, the management and the application layer. This approach try to decentralize the context acquisition on different devices. Also (Riva, 2006) proposes a middleware to provide context information on smart phone and mobile device. It provides multiple context provisioning strategies and distributed provisioning in ad hoc networks.

An example of Context Management System is *MobiComp* (Ryan, 2005). *MobiComp* has been used to store and access context data. Its core element is the ContextService acting as a store for context information and enabling coordination between the components of context-aware applications (Fig. 2. 1). The storage components behind the ContextService interface can be configured to support different scales of context-aware applications: simple stand-alone applications, multiple applications on a single device and applications spanning on multiple devices. In the last case, one or more networked servers make the context elements from heterogeneous sources accessible in a uniform way. Context elements take the form of a subject-predicate-object triple, relating an entity identifier to a named context value.

Three components exist for interacting with *MobiComp*: trackers, listeners and aggregators. The definition of this is the same of Producer, Consumer and Aggregator see above.

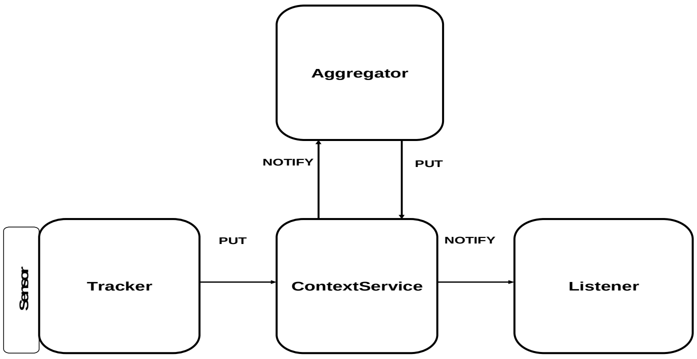


Fig. 2. 1 MobiComp infrastructure

Another example of Context Management System is the CAP (Salmon, 2009) developed from the Telecom Lab (TLab) of Torino. The CAP is a software platform for the management of context information. The CAP has realized a comprehensive and distributed context-aware system capable of aggregating and processing a variety of context information. The CAP has been designed according to the producer/consumer paradigm where some entities produce context, i.e. Context Providers (CP), while other entities consume context, i.e. Context Consumers (CC). These entities communicate with each other through a central entity named Context Broker (CB), which also provides some additional functions within the system Fig. 2. 2.

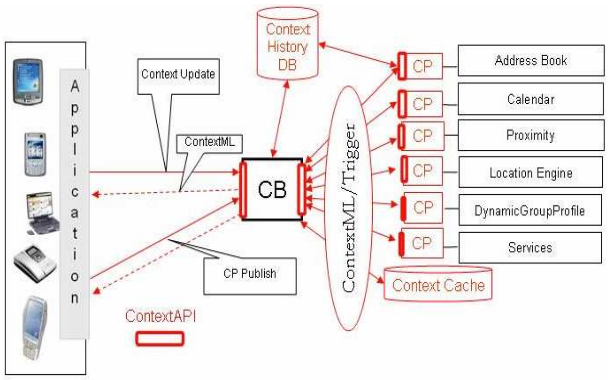


Fig. 2. 2 CAP Architecture (Salmon, 2009)

The Context Management System utilized during the research work is the SIB (Semantic Information Broker) (Toninelli, 2009). SIBs can collaborate with each other to create the Smart Space. Each SIB is defined as an entity (at the information level) for storing, sharing, and governing the information of one Smart Space. Access to the Smart Space is reserved to information processing entities called Knowledge Processors (KPs), which are the Producer, Consumer e Aggregator. Information sharing in the SIB is achieved by interaction of KP and the SIB via Smart Space Application Protocol

(SSAP) (Lappeteläinen, 2008). SSAP defines a simple set of messages that enable a KP to: join, query, update, subscribe to and leave the Smart Space.

2.1.2 Smart Environments Applications

In the last years, several Smart Environments applications has been developed in different domains. These applications utilize different Context Management systems and different data scheme.

Particularly active is the smart housing research field. The Smart Home concept is presented in (Ricquebourg, 2006). In this paper a smart home can be described as a house which is equipped with smart objects. Smart Objects make possible the interaction between the residential gateway and the inhabitants.

The Georgia Tech Aware Home (GeorgiaTechInstitute, 1998) is one of the most complete of these projects. The Aware Home Research is devoted to the multidisciplinary exploration of emerging technologies and services in the home. For this reason the initiative follow different research areas: services for aging people, for example utilizing support for family communication (*Digital Family Portrait*), providing a medication management (*Memory Mirror*) and using computer vision to estimate senior's risk for falling in natural situations (*Get Up and Go*); several tools for family are proposed, for example *AudioNotes* which is a message center for the family, applications to aid caregivers for children with developmental disabilities, *Baby Steps*, an application for helping parents track their child's developmental progress or *Pervasive Dietary Advisor (PDA)* which monitor the health of individuals with type 2 diabetes after they leave the hospital. The Aware Home try to satisfy the need of householders with respect to the energy consumption of various appliances. For this purpose a Smart Energy monitor that reuses existing infrastructure in the home has been developed.

The Adaptive House developed by the University of Colorado (UniversityColorado, 2010) is a prototype system in an actual residence. The home laboratory is equipped with an array of over 75 sensors which provide information about the environmental conditions. Temperature, ambient light levels, sound, motion, door and window openings are monitored. Actuators to control the furnace, space heaters, water heater, lighting units, and ceiling fans are present. Control systems in the residence are based on neural network reinforcement learning and prediction techniques. Some examples of what the system can or do are: predicting when the occupants will return home and determining when to start heating the house so that a comfortable temperature is reached by the time the occupants arrive; inferring where the occupant is and what activities the occupant is engaged in.

Another nice example of Smart Environment research focused on smart housing is the Massachusetts Institute of Technology House_n (MassachusettsInstituteTechnology, 2010). In this project new technologies, materials, and strategies for design are explored in order to make possible dynamic and evolving places that respond to the complexities of life. Major House_n initiatives are *The*

PlaceLab and the *Open Source Building Alliance*. The *PlaceLab* (Intille, 2006) initiative is a "living laboratory" residential home. The interior of the *PlaceLab* is formed by 15 prefabricated cabinetry interior components that can be rapidly reconfigured. Each of the interior components contains: a network of 30 sensors, an array of environmental sensors, including CO, CO2, temperature, and humidity, sensors to detect the on-off, open-closed, and object movement events, radio frequency devices to identity and detect the position approximate of people within the *PlaceLab*, microphones, a sophisticated video capture system processes images. Advanced features are provided, such as: context-specific feedback from people captured with standard PocketPC devices, using sensors to trigger and acquire information, activity recognition in order to trigger an action or intervention utilizing installed sensors or biometric and accelerometer devices worn by the user, dynamic control of the lighting system, environmental control.

The project EasyLiving (Brumitt, 2000), is a project of Microsoft Research. In this project researchers developed prototype architectures and technologies for builbing intelligent environments. The system works utilizing three models: the world model, which inputs are the sensors data, the User Interface service model, which inputs are the User Interface devices and the application model which is connected with the above twos. The features provided by the system are the tracking of users' movements and the room control to perform light and eating management.

The MavHome project developed at the University of Texas, (Das, 2002) is a home environment which detects home environmental states through sensors and acts upon the environment through controller. The major goal of the MavHome project is to create a home that acts as a rational agent. The agent seeks to maximize inhabitant comfort and minimize operation cost. To achieve these goals, the agent must be able to predict the mobility patterns and device usages of the inhabitants.

The Ubiquitous Home (Yamazaki, 2007) is a real-life test bed for context aware service experiments. The Ubiquitous Home has a living room, dining-kitchen, study, bedroom, washroom and bathroom, these rooms comprising an apartment. The Ubiquitous Home is equipped with various types of sensors to monitor living human activities. Each room has cameras and microphones in the ceiling to gather video and audio information. Floor pressure sensors installed throughout the flooring track residents or detect furniture positions. Infra-red sensors installed are used to detect human movement. Two RFID systems are installed in the Ubiquitous Home. Four accelerometers or vibration sensors are attached to the bedroom floor in four corners. To provide a service to users, the user context is considered. In the Ubiquitous Home, personal identification can be obtained from the active-type RFID tag worn by the resident or the face recognition by the visible-type robot camera.

One of Smart Home application are the Welfare Techno House (Tamura, 1995). The concepts of this experimental house is to promote the independence for the elderly and disabled people and improve their quality life.

2.2 New Vision of Smart Environments

The project SOFIA (Sofia, 2009) aims to develop a *cross-domain* interoperability platform and application development support for applications intended for different Smart Environments: personal spaces, indoor environments and smart cities. The physical environment from which the Smart Environments is created is heterogeneous and unknown. For this reason the process of creation of the Smart Environment starting from the physical one is an important problem to be solved in the domain of Smart Environment applications. Moreover, the subsequent management of the Smart Environments in another key problem. An innovative method to create and manage a Smart Environment is exposed in Paragraph 2.2.3. Before this in the following section is introduced the SOFIA vision of Smart Environment.

SOFIA proposes a platform for sharing interoperable information in Smart Environment applications. The platform is called the *Open Innovation Platform* (OIP) and its goal is to make *information* in the physical world available for smart services in embedded and ubiquitous systems. This implies a shift away from the classical focus on interoperability in the physical/service level towards interoperability at the information level. The information level can be seen as a set of information *Producers* and *Consumers*, shared information and its semantic data model. The OIP architecture is simplicity driven and it is made up of three distinct entities (Fig. 2. 3):

- Smart Space (SS) is a named search extent of information;
- Semantic Information Broker (SIB) is an entity (at the information level) for storing, sharing, and governing the information of one SS;
- Knowledge Processors (KP) is an entity interacting with the SIB and contributing and/or consuming content according to ontology relevant to its defined functionality.

The SIB acts as the shared information store for the OIP. It utilizes the Resource Description Framework (RDF), a triple based Semantic Web standard for expressing complex data as directed labelled graphs in combination with an ontology. As seen, the ontology contains all the definitions of the entities used within the SS and their properties which are also used to relate the entities with one another. The SIB provides an interface whose fundamental components are: *join*, *leave*, *insert*, *remove*, *query* and *subscribe*. The protocol used to communicate with the SIB is entitled the Smart Space Application Protocol, an application layer protocol based on XML. For a KP to interact with the SIB, it must first join the SS then it can insert or query for information as needed. The interoperability between KPs is provided when each KP is imbued with the knowledge from the relevant portion of the application's domain ontology.

To sum up, a simple, new definition of Smart Environment can be write: a Smart Environment is an unknown physical environment associated with a Smart Space.

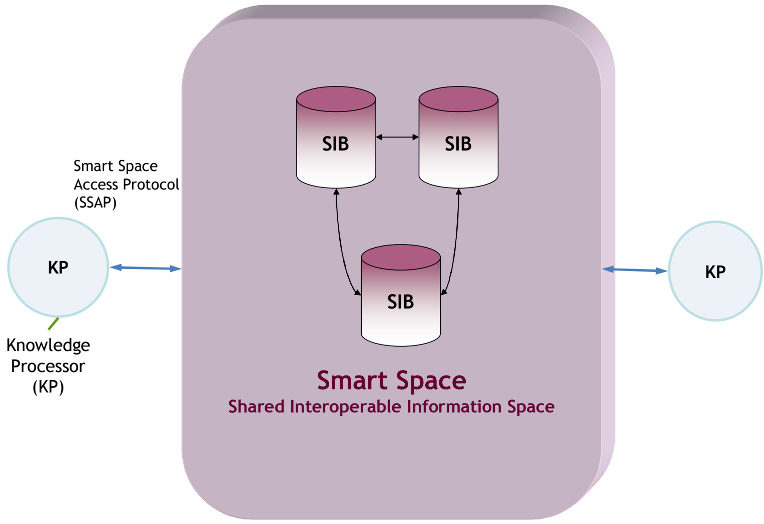


Fig. 2. 3 OIP logical architecture

2.2.1 An Application Design

Considering the introduced definition of Smart Environment, if the applications are based on a common, known vocabulary, they become interoperable. An example of interoperable application has been proposed in (Salmon, 2010). The following section is a part of this paper. In this case the applicative dominion is the medical one. This paper shows in a practical way the steps needed to design a Smart Environment application based on Smart Space. This is a two-step process: the entities involved in the application and the relationships between them must be modelled in an ontology, then the application must be partitioned into distinct KPs. When approaching the design of an ontology, the designer must take into account the information hierarchy in their application. The information interoperability is directly impacted by how expressive the ontology is.

The information which must be univocally represented in the proposed application are data derived from environmental sensors, *i.e.* temperature, location sensors, *i.e.* RFID, physiological sensors, *i.e.* users' hearth rate, skin temperature, and environment composition (Fig. 2. 4). If environmental and health data are made interoperable, then they may be abstracted to generate new knowledge, and thus effectively reused in innovative applications to the benefit of multiple institutions and users.

The scenario devised is depicted in Fig. 2. 4. The physical space is partitioned into "rooms" (room1 and room2). Temperature and relative humidity are sensed by Intel® iMote2 sensor nodes placed in each room. In the current implementation this data is transmitted to the shared information space through a room PC. Users wear a Zephyr Bioharness and a smartphone. The Bioharness senses skin temperature, heart rate and respiration frequency, and transmits this to the smartphone which, in turn, feeds the shared information store over a Wi-Fi connection. Each room is equipped with an RFID reader to perform location. An RFID tag is attached to each user's smartphone. When a person enters a room, his tag needs to be read by the reader that is located by the room entrance. This action is recognized and fed to the shared information space through the room-PC. This rather primitive but effective RFID based location system can be swapped out with more viable solutions in future deployments. Fig. 2. 4 also shows how data gathered from the users and from the environment may be used. The temperature and relative humidity data are abstracted into the thermohygrometric index, *i.e.* a bioclimatic index that is measure of the perceived discomfort level due to the combined effect of humidity and temperature conditions. Health monitoring and Alarm management are still rather rudimentary. The first tracks all of a user's properties, i.e. her health parameters together with the thermohygrometric index of the place where she is located. The alarm generator is meant to detect alarm conditions under specified policies and to publish them to the benefit of dedicated alarm handlers. Currently the alarm detection is threshold based and alarm handling is just a visualization.

The utilized ontology is shown in Fig. 2. 5. Our main entities, *i.e.* classes, are *Person*, *Environment*, *Alarm*, *Device*, and *Data*. The Person and Environment entities are self-explanatory. Alarms are entities characterized by an AlarmType, *e.g.* HeartRateAlarm, and in this case are related to Environments or to Persons. Devices are objects that can produce data or run KPs and are described by their characteristics, *e.g.* resolution, communication channels, MAC addresses. Data read by a sensor is represented by a literal value, *i.e.* the reading, a timestamp, the type of measurement, *e.g.* heart rate, temperature, humidity, the unit of measure and its privacy level. By modelling the data class in this way, we ensured that any KP consuming sensor data would be able to take advantage of new sensor types without having to rethink the KP.

The KPs were identified and modelled as shown in Fig. 2. 6:

- the Environmental Sensing KP publishes environmental sensor data to the system. When humidity and temperature data are inserted into the SIB they are associated with the room that is being monitored;
- the Physiological Sensing KP runs on a windows mobile smartphone. After configuration, data is captured from a Zephyr BioHarness. Every second heart rate, skin temperature and respiration rate are associated with a user and the information is inserted into the OIP;
- the Thom Index KP calculates the thermohygrometric index for every environment in the system. This index is a derivation of the humidity and temperature in the room and adjusts it to a new temperature that is more akin to that of what a person "feels". The KP subscribes to any temperature data, performs a check on the unit of measure, and inserts the new thermohygrometric data. The information is associated with a given environment based on the location of the sensors;

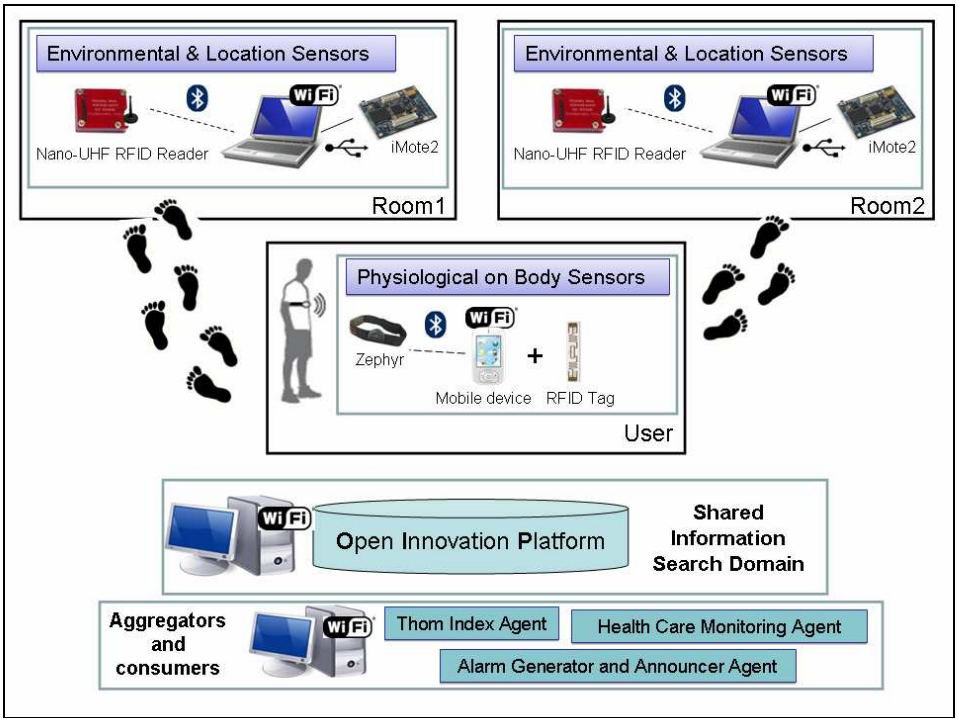


Fig. 2. 4 Smart Environment Medical Scenario

- the Location KP interfaces with the RFID readers so that when a person enters a room, he or she is associated with the new location. This KP also updates the location of any devices the person may have in their possession;
- the Alarm Generator and Announcer KP performs a search for all entities that have an associated safety threshold and subscribes to the relevant data. When the data falls outside of the threshold, an alarm is raised and placed in the SIB. This way any other KP wanting to perform some action is capable of doing so;

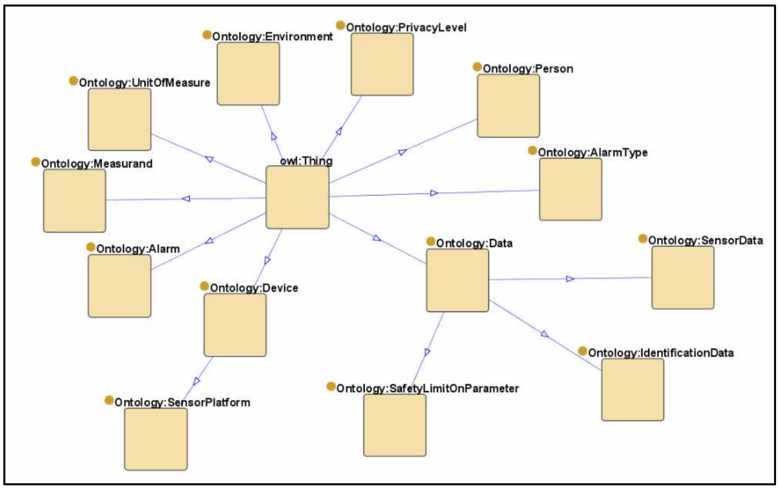


Fig. 2. 5 Medical Application Ontology classes tree

- the Health Care Monitoring KP allows the health care service to monitor a patient in real time. The KP allows the viewer to select from all the people available and then creates a subscription to all of their relevant data. It uses all of the data on the SIB, so not just physiological data is available, but also the person's environmental information as well. The KP visualizes instantaneous heart rate, skin temperature and respiration rate in addition to the user's location and its Thom Index.

2.2.2 Human Location Application

As seen the common factor of Smart Environment applications is the presence of highly heterogeneous hardware and software components that can seamlessly and spontaneously interoperate, in order to provide a variety of services to users regardless of the specific characteristics of the environment and of the client devices. This requires that the environment and the user must provide their contextual data, derived from sensors. For example in the application reported in the previous Paragraph the environment provide its temperature and humidity deriving these data from environmental sensors and user provide his or her hearth rate and skin's temperature deriving these data from physiological sensors. Another important data are the location of the user (see Chapter 5 for a definition). In other words, the Smart Environment has to be location-aware, in the sense that it must be able to know the position of mobile entities (people or devices) at any time in order to provide specific sets of services and information with different modalities of presentation and interaction. This contextual data is the one taken into consideration in this PhD work, developing a Pedestrian Positioning system which provides the position (see Chapter 5 for a definition) of a user which wears it. One of the requirements of this Pedestrian Positioning system is its integration in Smart Space.

The location in Smart Environment is a key problem in the several application dominions. In (Huang, 2009) is presented an ubiquitous indoor navigation service which provide an adaptive smart way to find support and enhance users with a new experience. A Smart Environment is created with a positioning module and a wireless module. In this case the Smart Environments do not follow the above mentioned definition and the Context Aware Management system is application oriented. Moreover, the contextual data are not modelled with ontology scheme.

(Coronato, 2009) presents semantic models, mechanisms and a service to locate mobile entities in the case of a Smart Hospital. It proposes a Semantic Location Service which can be integrated in any kind of environment as long as it is equipped with different positioning systems. The service exploits the integration of several positioning systems utilizing Semantic Web technologies. It is also presented a model to represent the localization information. This model is based on the concepts of physical and semantic locations.

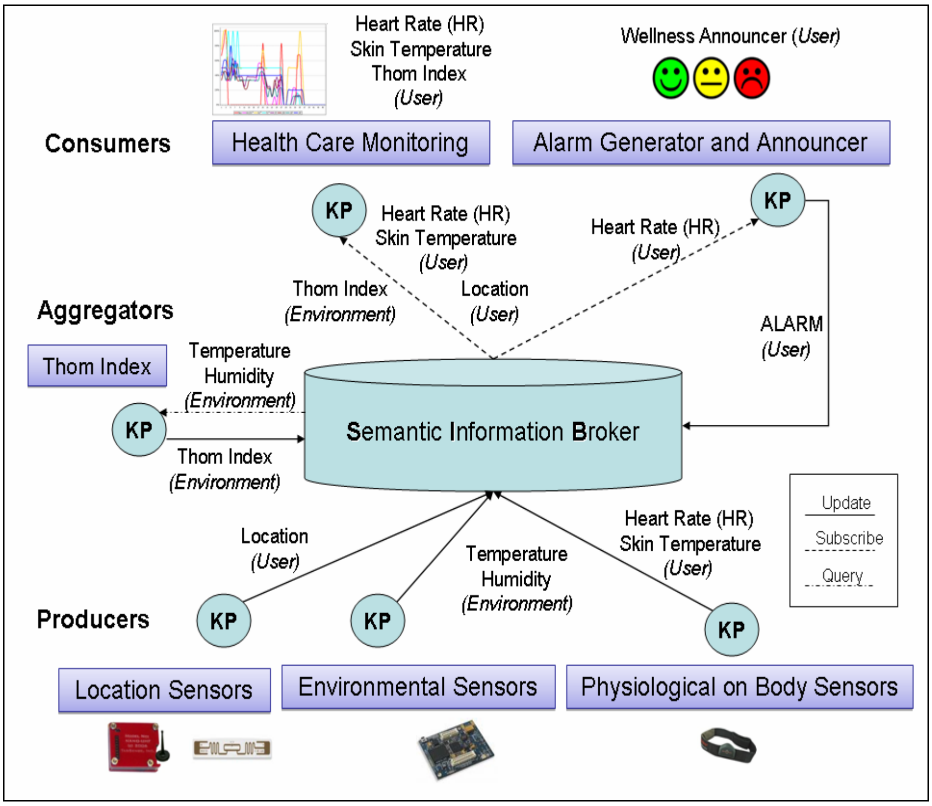


Fig. 2. 6 KP-SIB interaction

The location in a Smart Environment can be used for different application. For example: the user can access different sets of services while he or she is in different areas of the physical environment; the user can access a service with different modalities of presentation depending on his or her specific position; from the same service, the user can get different information depending on his or her position. The last example can be taken as a target example in the specific domain of museum application: visitors can get, on their mobile devices specific multimedia contents, such as audio or video contents, describing the artwork they are approaching or admiring. Considering this target example in the following section, the integration of the developed Pedestrian Positioning into Smart Space will be shown.

Considering the above mentioned practical two steps (Paragraph 2.2.1) to design a Smart Environment application based on Smart Space, the ontology has to be modelled. The entities involved in the application are indicated in Fig. 2. 7, divided in classes and subclasses. The *Device* class represents all the types of entity which can provide contextual data, *e.g.* Smart Phone, mobile devices and sensors. In fact subclass of the *Device* is the *Sensor Platform* class which represents all the sensors systems with contextual data. The class *Data* represents all the contextual information data. If this data arrive from a sensors system, the subclass of *Data*, *Sensor Data* represents this. The class *Environment* represent the composition of the environment. The subclass *Building Items* represents all the objects contained in the environment. *Unit of Measure* represents the unit of measure of the contextual data. The specific types of contextual data are represented by the class *Measurand*. The class *Person* represents the person in the Smart Environment.

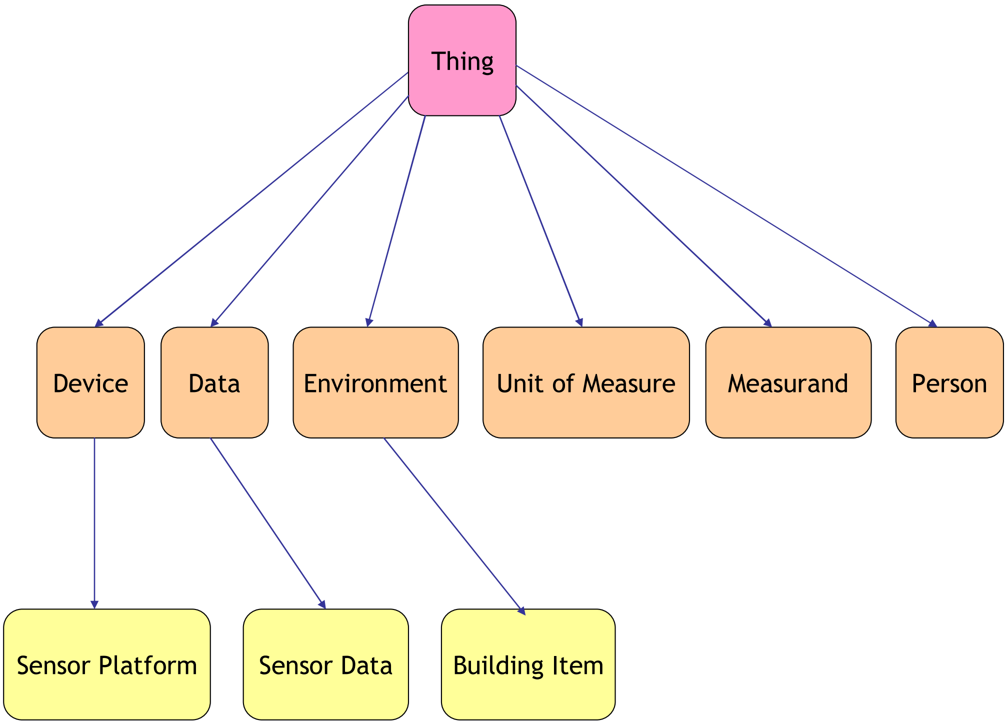


Fig. 2. 7 Location Application Classes tree

The Pedestrian Positioning system can be seen as an instance of the *Sensor Platform* (called MSB5 in Fig. 2. 8). The Sensor Data provided by the Pedestrian Positioning system are: the user's state (if the user is walking or not), the heading (the direction of movements) and the positioning (coordinate in the inertial reference system). These are instances of the *Sensor Data* class. Each of these Sensor Data can provide a *Measurand*, a *Unit of Measure* and a value which is a literal value. Fig. 2. 8 shows the instances of the classes with the relative properties. The yellow arrows represent the instances relationship. The composition of the environment is exposed in Fig. 2. 9. The example shows an environment composed of two rooms. Each room and the specific environment is subclass of the *Environment* class. Each room contains two items (statues and paintings), which are instances of *Building Item*. In the example each item is connected to a *Data* instance which represent the position of the item in the environment reference system: Painting_1 is connected to a *Data* instance, the measurand of which is an instance of the *Measurand* class.

Person_1 (istance of the *Person* class) wears the Pedestrian Positioning system.

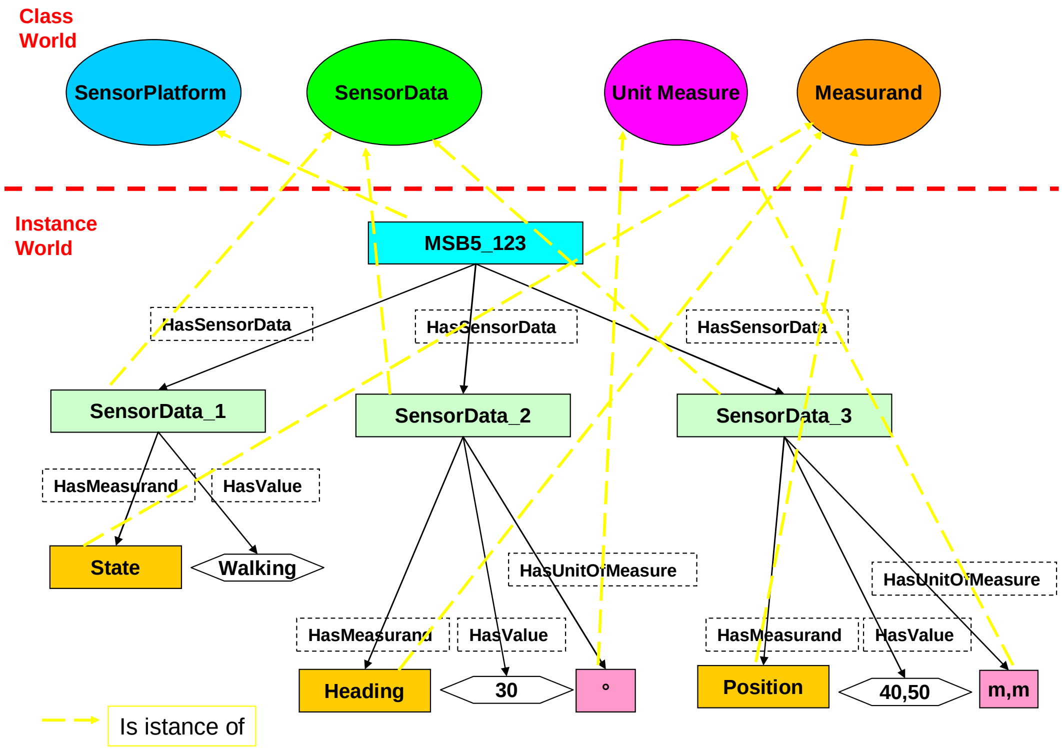


Fig. 2. 8 Location Application Ontology: instance world and class world-1

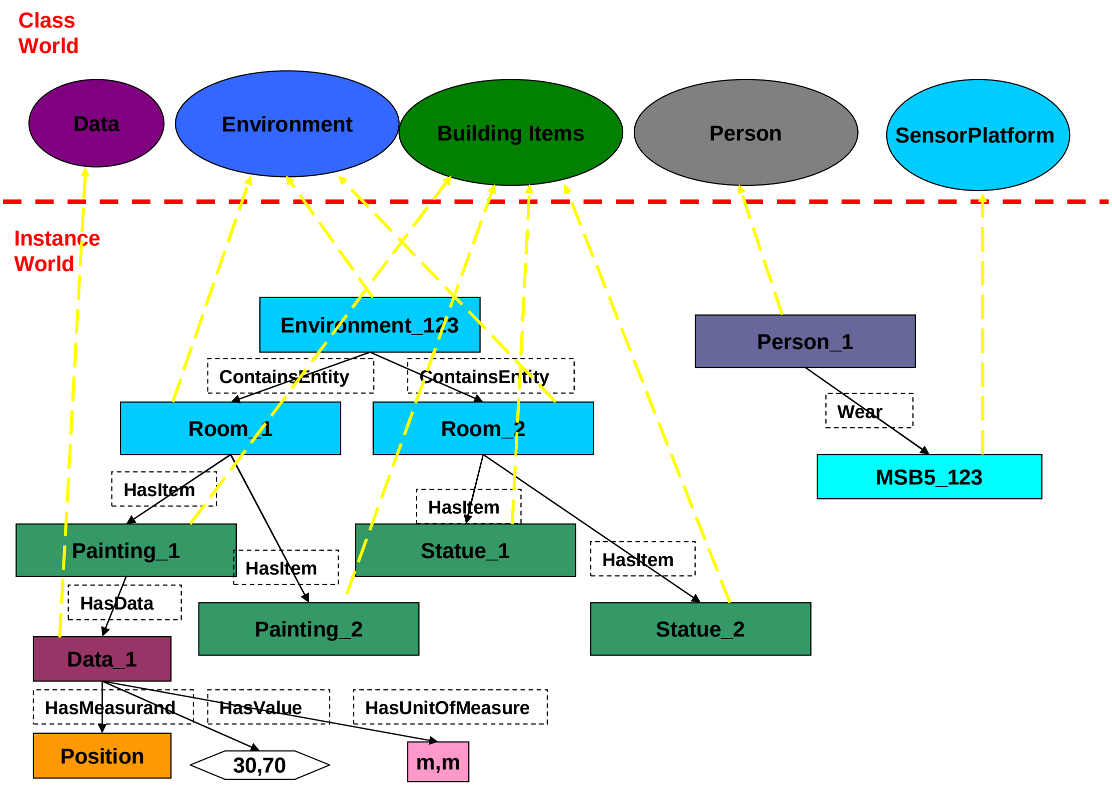


Fig. 2. 9 Location Application Ontology: instances world and class world-2

The Pedestrian Positioning system provides only the above mentioned contextual data. The aims of the integration of this system in Smart Environment based on Smart Space is to provide high level sensor data. According to the Paragraph 2.2.1, the second step in the development of Smart Environment application, is the definition of KPs. So, considering the example, an hypothetic KP can be developed to extract high level location data or to infer the state of the person walking in the environment. In Fig. 2. 10 the KP discovers that the person is near the Painting_1 and that the person is walking.

2.2.3 Creation of Smart Environment

As seen in the previous Paragraph, the existence of the Smart Environment is an hypothesis which has to be made in order to perform every Smart Environment application. For this reason the creation of the Smart Environment starting from an heterogeneous physical environment is the first step to take into consideration in every application. This creation has to be performed in an easy, fast and natural manner. Such a process has been studied by the University of Bologna research group working on the European project SOFIA. The creation of a Smart Environment starting from physical environment is performed through a process called “Smartification”. This process is patented and shown in (Bartolini, 2010). The patent shows also the easy management of the Smart Environment after its creation. Great relevance in this two processes (“Smartification” and Smart Environment management) has the device which helps the user in these tasks. In the patent it is called “Magic Smartifier”. As it will be seen in the Chapter 3, the device has all the characteristics to be a Smart Object, The development and the interaction methods between the user and the “Magic Smartifier” will be shown in Chapter 4.

The process of “Smartification” starts from a generic physical environment. The physical environment can be for example a building. This building can be composed of different rooms. It is supposed that every room or, generically speaking, every physical environment part, is univocally identified, *e.g.* from a barcode, a Semacode or RFID tag.

Each part of the physical environment, or *subspace*, contains several physical objects. To perform the “Smartification” process, every object has to be univocally identified, *e.g.* from a barcode, a Semacode or RFID tag, and the object has to be associated to the subspace of the physical environment in which it is contained. This task can be performed by the user by means of the “Magic Smartifier” which integrates the functionalities of reader for both subspace identifier and object identifier. After this association the *digital* copy of the object is created in the Smart Space. It is the “Magic Smartifier” that sends to the Smart Space the information that the object is contained in the physical environment subspace. The “Magic Smartifier” has to integrate also communication functionalities. For an example of the user-“Magic Smartifier”-Smart Space interaction model see Chapter 4.

The *digital* copy of the physical object in the Smart Space contains the location information of the object. Other characteristics can be added at any time.

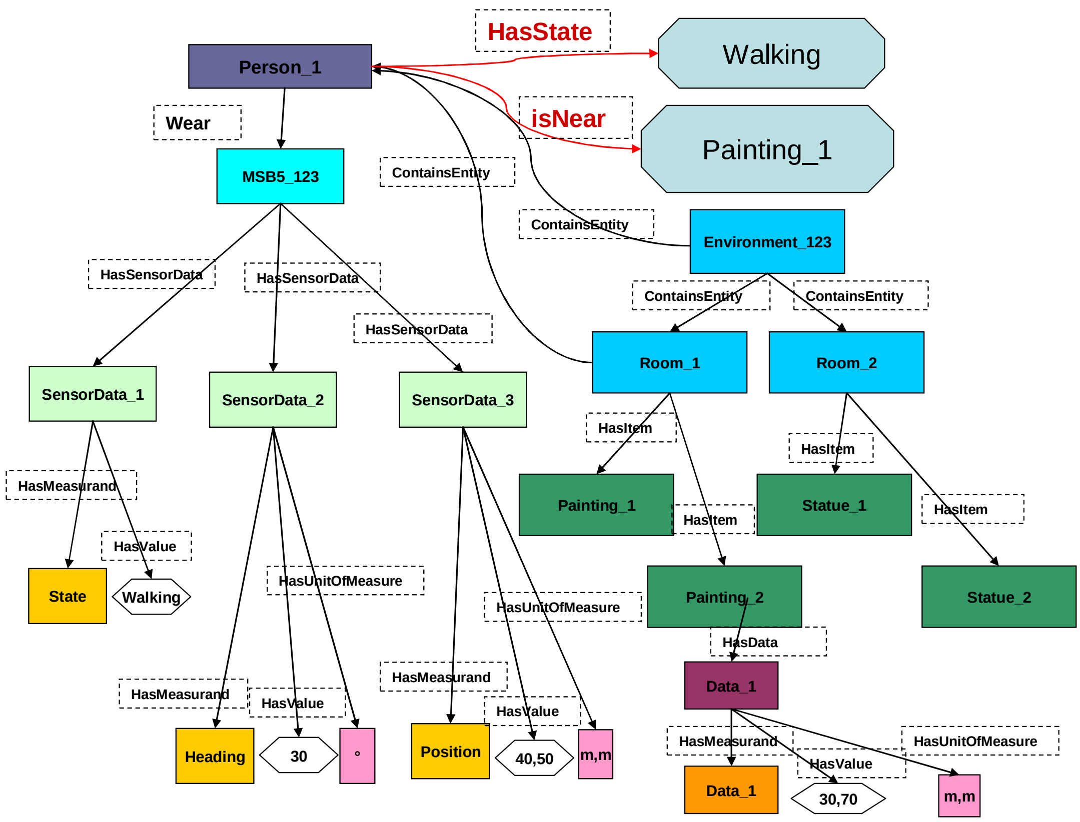


Fig. 2. 10 Integration of Pedestrian Navigation System in Smart Space

For example the typology of the object, which can be discovered by means of a camera and visual objects recognizer algorithms, or the status of the object, *i.e.* if the object is working or not, if it is broken or not.

The last case can be seen as an example of Smart Environment management: when a user sees that an object is broken, he or she points out to the Smart Space its condition. This task can also be performed by the user by means of the "Magic Smartifier". The user can point out that the physical object, which its *digital* copy is present in the Smart Space, is broken, identifies the object and then sends to the Smart Space this information. Potentially, the type of object's fault can be assigned to the above information, selecting the fault type, for example by means of gesture recognition algorithms.

The "Smartification" process can be seen as the creation of a *digital* copy of the physical environment.

Part I

INTERACTION IN SMART ENVIRONMENTS

Chapter 3

RELATED WORKS ON INTERACTION

This Chapter shows an overview on interaction concepts that support user interaction techniques and user interaction metaphors in different Smart Environment situations and different users regarding individual preferences and characteristics. Interactions are created to support the Smart Environment and the user. Interaction in the context of Smart Environments can be either active (explicit) interaction or passive (implicit) interaction by means of ambient sensors and contextual data tracking. The goals of interaction are: supporting adaptative interfaces of devices on user's preferences, supporting of self-configuration of devices to collection of interaction devices, providing a loop for interaction with the environment and feedback loops for information gathering from the environment.

In Paragraph 3.1 the concepts of Human-Computer interaction are explained and definitions of Interaction are reported. In particular, the rules that a designer have to follow to design an object are exposed from the Interaction point of view. In Paragraph 3.2 an excursus of the Interaction paradigms is shown. In Paragraph 3.3 the state of the art of the Interaction techniques and technologies is reported. In particular the works that utilize Inertial Sensors and RFID technologies are presented. The definition of Smart Object, an overview of the possible applications in which it could be employed and the state of the art of the utilization of Smart Objects as Interaction devices is shown in Paragraph 3.4.

3.1 Natural Interfaces Principles

The Human-Computer Interaction (HCI), called also Human-Machine Interaction, is the study of how people can interact with computers. That is, it is the study of how a program can communicate with a person. This point of view is important because is a duty of the human, which is most intelligent, to try to infer the behave of machine and not vice versa.

The interaction systems are characterized b different type of interaction with the user. In the context of Smart Environment, the interaction can be divided in explicit or implicit interaction. The latter is when the user intentionally interact in an active way with the system or environment. The former is when the interaction is performed by means of ambient sensors and contextual data.

The story of Human-Computer Interaction has influenced the project of machines which are utilized every day by the people. In fact, nowadays, the computers, or the instruments, utilize more and more windows, icons and menus. This kinds of metaphors must derive from the communication between people. This communication is defined *natural*. The *natural* communication derives from the everyday experience: people communicate in a natural way by means of gestures, expressions, movements and they discover the world utilizing the sight and manipulating the physical matter. The eventual disappearance of technology is another key factor of *natural interaction*.

HCI can be useful for the evaluation of systems which can interact with people in a usable, reliable and easy way. One of the most important researcher in the field of the design of systems which are easily usable by people is Donald Norman. In its famous work *The design of everyday things* (Norman, 2002), he introduces the principles which designers must take into consideration to make devices usable. The usability is defined by the ISO (ISO/TR 16982:2002, ISO 9241) as a qualitative attribute that assesses how easy user interfaces are to use. The word usability also refers to methods for improving ease-of-use during the design process. It is composed of: learnability (how easy is it for users to accomplish basic tasks the first time they encounter the design?), efficiency (once users have learned the design, how quickly can they perform tasks?), memorability (when users return to the design after a period of not using it, how easily can they re establish proficiency?), errors: (how many errors do users make, how severe are these errors, and how easily can they recover from the errors?), satisfaction (how pleasant is it to use the design?).

In (Norman, 2002) it is proposed a logical structure for the process of design necessary to take into consideration the above usability definitions. The stages of design are seven, and each one correspond to a stage performed by a human to do a task:

- forming the goal: determine the function of the device
- forming the intention: tell what action are possible
- specifying an action: determine mapping for intention to physical movements
- executing the action: perform the action

- interpreting the state of the world: tell if system is a desired state
- evaluating the outcome: tell what state the system is in

From these stages, Norman deducts the principle of good design, *i.e.* what the designer has to take into account to make the system usable:

- visibility: by looking at it, the user can tell the state of the device and the alternative for action
- a good conceptual model: the designer provides a good conceptual model for the user with consistency in the presentation of operations and results and a coherent, consistent system image. The user is able to know how the system works without big effort
- good mapping: the user can determine the relationship between actions and results, between the control and their effects and between the system state and what is visible
- feedback: the user receives full and continuous feedback about the results of actions.
- affordance: to provide effective, perceivable affordances is important in the design because people have the ability to discover and make use of these in novel situations.

The most important requirement for a Human-Machine interaction is how these two entities communicate. Norman in (Norman, 2007) introduces five rules for this kind of communication which designer has to take into account. This rules derive from the above, but the point of view is the communication:

- keep things simple: people prefer short messages in the communication. So devices have to provide non-ambiguous messages, and preferably not written ones;
- give people a conceptual model: people want something their minds can understand. The best way to convey the conceptual model is through natural communication system;
- give reasons: the explanations have to be consistent with the conceptual model. People want to see things and not trust on devices;
- make people think they are in control: when people have a good conceptual model with good feedback, it makes them feel as if they are in control, even when they aren't;
- continually reassure: people have to be reassured with feedback saying what is happening.

In the analysis and development of interaction devices, this simple but efficient rules have to be considered to give the impression to the user that the device reacts to his inputs and that the device is under his control.

3.2 Interaction Paradigms

The Interaction Paradigms describe the conceptual model and principles of the interaction between people and machine. Valli in his WhitePaper (Valli, 2007) addresses the problem of the relationship between humans and technology-enhanced spaces. Several artefacts are described as exemplifications of the interaction's theory.

The following list is an overview of some Interaction Paradigms:

- Pen-based Interaction: In the pen based interaction paradigm the user utilizes a stylus to interact with a screen for example of personal digital assistants (PDA) or tablet PC. The interaction's birth coincides with the birth of graphical screen and the possibility to interact with them. One of the first interaction works has been developed by Sutherland (Sutherland, 1963) in its PhD thesis in which a lightpen is utilized to interact with cathode ray tubes. (Iannizzotto, 2007) describes a pen-based user interface for easy and natural user interaction with a wall projection display (VisualPen). (Jetter, 2008) introduces the novel user interface paradigm ZOIL (Zoomable Object-Oriented Information Landscape). ZOIL is aimed at unifying all types of local and remote information items with their connected functionality and with their mutual relations in a single visual workspace as a replacement of today's desktop metaphor.
- One-handed Interaction: One handed interaction is the predominant interaction paradigm for mobile handsets. The typical way of operation is through a combination of buttons and a display. The requirement to work one-handedly excludes the usage of a pen, as you need two hands to hold the device and the pen in general. EnChoi is following the one-handed interaction paradigm, as operations are designed to allow a touch-screen text input with the bare thumb of the same hand that holds the device. Users can slide a letter ribbon up and down, whereby language statistics control for the size of the individual letter fields.
- WIMP Interaction: Windows, Icons, Menus, Pointer (WIMP) was first introduced in 1962 (Engelbart, 1962). The name originates from the utilized entities: Windows, Icons, Menus, Pointer. Operation is done mainly by utilizing a general pointing device, typically a mouse, to access and manipulate information on the screen by pointing, clicking and dragging.
- Form-based Interaction: It basically is a direct adaptation of form filling on paper on computerized systems. It is still very present in web applications, where users must fill in form fields in their browser. An advantage of the paradigm is that it is easy to understand for the users. On the other hand it is often implemented in a way that makes it difficult for users to make free choices on what to do first, or difficult to operate in presence of partially unknown information.
- Zooming user Interaction: Zooming user interface is often a sort of 3D GUI (Grafical User Interface) environment, in which users can change the scale of the viewed area in order to see more detail or less. (Conante, 2010) is an example of Zooming user Interaction for handheld projectors that is controlled by direct pointing gestures
- Haptic Interaction: Haptic interfaces (Michelitsch, 2004) are interfaces which depends on the users' force, such as force-feedback joysticks and vibrotactile mice. There are two types of haptic interface: those operating on the sense of touch (rely on vibrotactile stimuli) and those operating on the kinesthetic sense (the force is exerted by means of electric motors coupled to the

control). The SensAble Phantom (SensAble, 2010) is an example of kinaesthetic Haptic interface. It works like an inverted robot arm, that a user moves around the robot's endpoint. The robot simulates forces according to a virtual simulated area.

- Tangible Interaction: with tangible interfaces a user interacts with digital information through physical environment. A central characteristic of tangible interfaces is the seamless integration of representation and control (Fitzmaurice, 1995; Ishii, 1997). Tangible user interfaces are often used as input channels in other paradigms. For example, in ambient interaction, Tangible User Interfaces introduce physical, tangible objects that augment the real physical world by coupling digital information to everyday physical objects. The system interprets these objects as part of the interaction language. Physical follow-me tokens (Van de Sluis, 2001b) is an example of Tangible Interaction. The interaction with the tokens is very simple. Users only had to pick up a token at the initial location and to put down at the destination location. This was enabled by RFID technology. TANGerINE (Baraldi, 2007) is a tangible tabletop environment where users manipulate smart objects in order to perform actions on the contents of a digital media table.
- Wearable Computing Interaction: Wearable computers are computers that are worn on the body. They are especially useful for applications that require computational support while the user's hands, voice, eyes or attention are actively engaged with the physical environment. An example of wearable computer is the Thad Starner's eyeglasses (Starner, 2010). Another example of wearable devices is the Eurotech’s Zypad (Eurotech, 2010), which combines the same features of a standard computer with a device that provides the convenience and ergonomics of a wrist worn instrument.
- Anthropomorphic Interaction: In the anthropomorphic interaction the system is like an extension of human body. Anthropomorphic interface can be based on vision but also based on speech recognition. The system has to interact in the more naturally way, as if the user is interacting with an other human. Philips Research created the concept of an on-screen animated dog, which has been developed to facilitate voice control in a home entertainment system (Van de Sluis, 2001a). Further examples of anthropomorphic user interfaces have been developed in the course of the Projects EMBASSI and SmartKomn (Elting, 2003; Wahlster, 2006). Both projects allowed also for multimodal interaction in which the users can combine spoken commands like "record that" with pointing gestures that identifies the objects for recording.
- Virtual Reality Interaction: Virtual reality is a technology which allows a user to interact with a computer-simulated environment. Users can interact with a virtual environment through the use of standard input devices such as a keyboard and mouse, or through multimodal devices such as wired gloves or mechanical arms (Polhemus, 1969). In (Heim, 1994) are identified seven different concepts of Virtual Reality: simulation, interaction, artificiality, immersion, tele-

presence, full-body immersion, and network communication. An example of Virtual Reality application is called “Eat me and Drink me” (Bartneck, 2008) developed at Eindhoven University of Technology. The installation tries to manipulate the visitor's relative size in comparison to the environment.

- Ambient Interaction: Ambient interaction communicates information at the user taking advantage of the periphery of human attention. The concept of ambient interaction is based on the idea that humans monitor well sound or images in the periphery of their attention. Cues to the humans can be performed utilizing ambient light, sound, airflow...(Weiser, 1996). Prominent changes in these ambient cues will be noticed by users and may trigger them to have a more explicit interaction. The basic idea of ambient interaction is that the physical environment of a user is used as a vehicle for digital interaction. The user either communicates voluntarily with a device in order to extract detailed information from it or she may be discovered by the ambient. One example developed at Philips Research is the concept of HomeRadio (Eggen, 2003). The HomeRadio concept is based on the idea that home activities can be coded by the corresponding utility streams they generate (gas, electricity, water, communication and information). This coded information is broadcast and family members can tune in to this stream.
- Brain Computer Interface: The brain computer interface (Dornhege, 2007) is a direct communication from the human brain to a computer. (Van Aart, 2008) designed an headset for neuro-feedback therapy in the home environment.
- Enactive Interaction: Enactive (Bennett, 2007) is a form of interaction realized in the form of sensory-motor responses and acquired by the act of "doing". It is a form of cognition inherently tied to actions, capable of directly conveying a non-symbolic form of knowledge. Enactive is one of the three possible types of knowledge used when interacting with the world: symbolic, iconic and enactive. That is, once it is learnt, it can be reproduced very easily also after years without too much mental effort. Illuminating Clay (Piper, 2002) is an example of an enactive interface. While users model a clay landscape on the table the changing geometry is captured in real time by a laser scanner. The captured data is fed into an analysis, the output of which is projected back on the clay.

3.3 Interaction Techniques and Technologies

In this Paragraph, after a list of the most common, standard and frequently used techniques, it will be presented the two technologies utilized in the developments of a Smart Object as support of Smart Environment, which will be explained in Chapter 4. This list is only an high level overview and it is by no means exhaustive.

The point of view considered in this overview of interaction techniques is the usability and human-centric one. The characterization will divide the technologies which are utilized in the interaction's path from the user to the device, and from the device to the user.

- Visual: the visual modality can be utilized in both directions. In particular activity detection has various applications in interaction, such as counting the number of person and detecting their motion, body posture recognition, facial expression and gaze recognition.

  In the field of human detection, many methods focus on pedestrian detection. In (Dalal, 2005) histograms of gradients provide excellent performance. (Yilmaz, 2006) reviews the state-of-the-art human tracking by video camera methods, classifies them into different categories and identifies new trends. Two different approaches can be used to detect user's position: cameras in the building or cameras with the user. The implementation of a vision-based system for recognizing pedestrians in different environments and locating them with the use of a Kalman filter is shown in (Bertozzi, 2004b). A recent overview of posture estimation by video camera is presented in (Jackson, 2008).

  Regarding the interaction's direction from devices to human, one of the simplest ways to put information from the system to the user is via linguistic textual expression. For this, text displays are widely diffused. Another interaction common to windowing and non-windowing systems are menus.

  Direct manipulation is a new form of interaction which is involved in the two directions (Shneiderman, 1983). It involves the continuous representation of objects of interest, and rapid, reversible, incremental actions and feedback. An example of direct-manipulation is resizing a window by dragging its corners or edges with a mouse, or erasing a file by dragging it to the recycle bin. A basic approach is presented in (Tonouchi, 1992).

  The development of gesture recognition and hand tracking techniques has enhanced the direct manipulation techniques. Multi-touch interfaces are spreading in modern mobile phones (iPhone).
- Smell: Scents constitute an important source of information for people during their daily routines. The importance of the sense of smell has been largely ignored by the general audience and also by science. There are few work on interaction with smell. An example is the game "Fragra" (Mochizuki, 2004) which combines visual information together with smells.
- Auditory: Auditory-based interaction has sound feedback or alarms, speech recognition and speech synthesis. In particular the speech recognition is an open field of research. Speech recognition is in particular based on statistical approach (Rabiner, 1993), *e.g.* utilizing Markov Model. Opposite to the speech recognition is the speech synthesis. This is the process of generating audible speech signals from symbolic representations of speech, such as texts.

- Haptic: all the interfaces in which hands and fingers are involved, such as keyboards, mice, cursors, joysticks and pens, are haptics. Concerning the text inputs, several methods are present. Many of them work with numeric keypad and redundancies in natural language (MacKenzie, 2001). Other methods have been designed for text entry by pen, for example in tablet PCs and electronic whiteboards (Perlin, 1998).

  To increase the naturalness of interaction, hand gesture recognition is important. The first steps in hand gestures recognition have been done in the late 70s at MIT with the Put-that-there project (Bolt, 1980). Typical sensors used in gesture recognition are inertial and bend sensors.

  Considering the interaction from device to human the tactile sense can be seen as the most intuitive feedback. The direct stimulus to provide depends on the part of the user's body to be stimulated. (Johansson, 1979) shows a study of skin stimulus in hand's skin. Technologies typically used are: electromechanical actuators, pneumatic or hydraulic actuators, piezoelectric actuators, Shape Memory Alloys (SMA), Dielectric Elastomer Actuators (DEA), Electro Active Polymers, MEMS actuators for Tactile Displays, Vibrating motors, solenoids or voice Coil, thermoelectric elements.

The technologies involved in interaction are several and of different nature. In (Ailisto, 2003) three examples of physical interaction from human and devices are proposed.

In the following paragraph only some references of works which concern interaction by means of RFID and inertial sensors are reported. These two technologies are utilized in the Smart Object developed and will be explained in Chapter 4.

3.3.1 Inertial Sensors in Interaction

Inertial sensors (accelerometers and gyroscopes) are motion sensing devices based on moving mass. An explanation of Inertial Sensors will be given in Chapter 5 and 6. They are commonly used to enrich handheld device functionality, for instance to change the display orientation or to recognize gestures.

In the first case, the inclination angles of the mobile devices can be easily measured by means of accelerometers. For example the iPhone can switch the display view according with the orientation of the device. Thanks to their reduced size, inertial sensors are often embedded into video games controller (Wii or Nintendo) or in tangible interfaces (Baraldi, 2007).

(Rekimoto, 1996) introduces new interaction techniques for small screen devices such as palmtop computers or handheld electric devices, including pagers and cellular phones. The proposed approach uses the tilt of the device as input. In (Hinckley, 2000) a two axis accelerometer, a touch sensor and an infra-red sensor are used to implement three demonstrations, such as *Tilt scrolling & portrait/landscape modes* in which users of mobile devices can tilt the devices to scroll the display. In (Eslambolchilar,

2004) a three axis accelerometer attached to the serial port of the mobile device is used to solve the problem of large document and small display, acting as a speed dependent automatic zoom mechanism.

A tilt-controlled photo browsing method for small mobile devices is presented in (Cho, 2007). The implementation uses continuous inputs from an accelerometer, and a multimodal (visual, audio and vibro-tactile) display is used as output.

Accelerometers can also be used in gesture recognition. In (Wan, 2008) the design and implementation of a HCI using a small hand-worn wireless module with a 3-axis accelerometer as the motion sensor is presented. (Kallio, 2006) proposes an accelerometer-based gesture control based on Hidden Markov Models.

An hybrid solution on tilting and gesture recognition is presented in (Crossan, 2004) in which a study that examines human performance in a tilt control targeting task on a PDA is described. A three-degree-of-freedom accelerometer attached to the base of the PDA allows users to navigate to the target by tilting their wrist in different directions.

3.3.2 RFID in Interaction

Radio-frequency identification (RFID) is an automatic identification method, relying on storing and remotely retrieving data using devices called RFID tags or transponders. The technology requires cooperation of an RFID reader and an RFID tag. This technology can be used in several applications: in the logistic process, in health care applications, in the customer process, in vehicle applications, in navigation applications, *e.g.* as support of museum guide (Salmon, 2008). In Chapter 5 the RFID technology is presented as localization technology.

An important vision of the usage of the RFID technology is the identification of every element in physical space, *i.e*. users, devices, objects and environments. In fact, utilizing the RFID unique identifier allows to tag "every square centimetre on the earth, creating an addressable continuum of computers, sensors, actuators, mobile phones; *i.e.* any thing or object around us." (EPOSS, 2008).

Regarding the Human-Computer Interaction, one of the domains in which RFID interaction is applied is that of museum sightseeing. (Mantyjarvi, 2006) presents a mobile museum guide which uses RFID and a two-axes accelerometer to enable physical object selection. The interaction technique is called *Scan and tilt* and uses multiple modalities, combining gestures, physical selection, location, graphical and voice interaction. In particular, physical selection is obtained by scanning RFID tags associated with the artworks, and tilt gestures are used to control and navigate the user interface and multimedia information. RFID, Radio Frequency and InfraRed are used in (Välkkynen, 2003) to implement one of the three approaches (*pointing*, *scanning* and *touching*) presented for physical user interaction. The paper suggests that for any tagging technology these three paradigms should be implemented to provide optimal support for natural interaction with physical objects. In (Bravo, 2008) the use of RFID technology to make daily activities interactive using tags embedded into day to day objects is compared with the use of Near Field Communication technology. (Salmon, 2009) presents a novel approach to assist a group of users to access and control personalized context based services by means of natural interactions. The group creation and the service activation are both based on the use of RFID tags. Each user can join a group by placing her personal tag on an RFID reader. Once the group has been created each available service, *e.g.* pictures slideshow, media player, recommender, can be activated and deactivated through ‘service’ RFID tags. Some services can also be controlled by acting on a Smart Object able to detect simple movements, *e.g.* roll forward, roll backward, tilt left, tilt right.

A demonstration of the concept of Smart Object utilizing RFID in the supply chain is reported in (Cea, 2006). The use of RFID is necessary because they posses a unique identifier, they can contain information, they can take care of theirself and they can communicate with the environment.

3.4 Smart Objects in Interaction

Smart Objects are small computers with sensors, actuators and a communication capability, embedded in other objects or stand-alone. Smart objects enable a wide range of applications in areas such as home automation, building automation, factory monitoring, smart cities, structural health management systems, energy management, and transportation. Practically, talking of Smart Object is like talking of a class of portable devices with not well defined functionality, but certainly characterized by:

- connectivity: Bluetooth, ZigBee, GSM, Wi-Fi…
- sensors: switches, buttons, knobs, position sensors, temperature sensors…
- actuators: LEDs, displays, loudspeaker, vibro-tactile motors…

Until recently, Smart Objects were realized with limited communication capabilities, such as RFID tags, but the new generation of devices has bidirectional wireless communication and sensors that provide real-time data such as temperature, pressure, vibrations, and energy measurement. Smart Objects can be battery-operated, and typically have three components:

- CPU
- memory
- a low-power wireless communication

Due to the extreme versatility of applications and typology, Smart Object are very spread in academic and industrial research.

One of the first group working on Smart Object was the Things That Think (TTT) consortium at MIT Media Lab (MIT, 1995). Things That Think began with the goal of embedding computation into both the environment and everyday objects.

A nice example of personalized Smart Object is the *Chumby* (Chumby, 2006). *Chumby* takes user’s favorite contents on the Internet and delivers them to the user in a friendly way. Another nice example of everyday Smart Object is the *MediaCup* (Beigl, 2001). This is an ordinary coffee cup augmented with sensors, processing and communication. The cup is able to sense its movement and temperature and to share these information to support context-aware systems. An evolution of the embedded platform utilized in *MediaCup* is exposed in (Beigl, 2003), called Smart-Its. This platform has been used in several work to explore how augmented artifacts can cooperatively reason about their situation in the world (Strohbach, 2004) and to track activity through weighting surfaces (Schmidt, 2003).

Smart objects are used to improve social interaction. For example a useful example is *Smart Ring*. Each *Smart Ring* stores the user details, transferred there via a digital business card the size of a credit card. For example, to pass along user's details to a new business associate, it is necessary to shake hands instead of handing over a traditional business card. Another example is *Lover's Cups* (Chung, 2006). Cups are linked in couple. When both cups are used at the same time they provide a visual feedback to the user in order to reinforce social ties between people.

Smart object carried or worn by the user can be used to perform activity recognition in an unobtrusive manner by analyzing how they are used. For example, the Intelligent Gadget is a smart object for personal life logging (Jeong, 2008). The Sensor Button is a wearable sensor node with the form factor of a button that can be unobtrusively integrated into user garment to perform activity recognition (Roggen, 2006). The Sensor Button integrates an accelerometer, a microphone and a light sensor together with a 16 bits microcontrollers and a wireless transceiver.

Guide lines in implementation and integration of Smart Objects are exposed in (Kranz, 2005) in which are identified issues related to the hardware and software prototyping o Smart Object.

In the dominium of Smart Environment, the management of the physical environment is particularly important. As seen in Chapter 2, this task can be performed once the Smart Environments is created. The process of creation of the Smart Environment starting from the physical environment is called in this work "Smartification". In this process, of great importance is the object by which the environment is "Smartified". In this work this object is called "Magic Smartifier" and has the function not only to "Smartify" but also to manage the built Smart Environment. For its functionality and characteristics, the "Magic Smartifier" can be seen as a Smart Object. The description of such Smart Object will be given in Chapter 4. In literature only few works exist, concerning the development of Smart Object utilized in the management of the Smart Environment. For example in (Guo, 2007) a system which search and localize physical artefacts in smart indoor environment, called Home-Explorer, is proposed. Home-Explorer handles not only objects provided with a smart sensor but also all the other objects. Particularly, it uses the physical context from smart objects to derive the information of non-smart objects. A specific module named Sixth-Sense is used to fulfill this task. (Kawsar, 2007) reports the experience with sentient artefacts to rationalize intelligent environment. Sentient artefacts are everyday objects augmented with digital services. The paper presents design principles of sentient artefacts. On the other hand, (Satoh, 2008) presents a location aware communication approach for Smart Environment but not by means of Smart Objects. It utilizes a location model by which there are relationship between physical objects and places.

The difference between the above approach and the “Smartifier” in the fact that the above mentioned method to manage the Smart Environments needs an ad-hoc structure and ad-hoc devices to perform the managing task. In our vision the managing of the environment can be done utilizing all the sensors which provide the required data in a well defined format. Moreover, the above methods hypothesize that the Smart Environment already exist. The “Magic Smartifier” is the creator of the Smart Environment.

Chapter 4

DESIGN OF A SMART OBJECT FOR HUMAN INTERACTION

In this Chapter the design of a particular type of Smart Object is presented. This Smart Object, called "Magic Smartifier" has been studied by the University of Bologna research group working on the European project SOFIA. The duty of this Smart Object is the creation and the management of Smart Environment starting from physical environment, as seen in Chapter 2 where the process of "Smartification" is explained. The Smart Object must be used by humans, so the Natural Interaction Principles are taken into account.

Paragraph 4.1 reports the design of the Smart Object, its components and its architecture. The Interaction methods necessary in the utilization of the Smart Object are also exposed.

In Paragraph 4.2 an approach to the design of power supply sub–system for Smart Object is presented.

4.1 Smart Object for Smart Environments Management

As seen in Chapter 3, the management of physical environments is particularly important. The creation of a Smart Environment starting from the physical environment is one of the method to manage such an environment in an easy way. A type of process to create the Smart Environment starting from the physical environment has been studied by the University of Bologna research group working on the European project SOFIA. This process has been called "Smartification". The object utilized to perform the "Smartification" is critical to achieved the process. This object is called "Magic Smartifier" and has the function, not only to "Smartify" but also to manage the built Smart Environment.

As seen in Chapter 2, to create the Smart Environment, it is necessary to create the digital copy of objects. This digital copy will be stored in the Smart Space. The digital copy of an object is identified through an univocal identifier, which is stored in the Smart Space. The second information stored in the Smart Space when the environment is "Smartified" is the location of the object in the Smart Environment. If for example the physical environment is a building floor, the location of an object could be the room of the floor in which the object is.

The digital copy of the object during the "Smatification" process is characterized by the couple: (Univocal Identifier, Location). Additional characteristics, such as the typology of the object, its state and if necessary an high level location, can be later stored in the Smart Space.

Therefore, to "Smartify" the environment it is necessary:

- to couple the object with an univocal identifier
- to identify the location (*e.g.* room) of the object
- to send the couple (Univocal Identifier, Location) to the Smart Space.

To do the above steps, RFID technology has been chosen. The whole "Smartification" procedure has been shown in Chapter 2.

The managing of the Environment involves several actions. The first action implemented is the "Selection":

- a visible object which necessitate an intervention is selected
- the type of intervention is selected by means of *gesture* interaction
- the type of intervention needed is sent to the Smart Space.

The do the above steps, accelerometer board which identifies the gesture has been chosen. The whole "Selection" procedure has been shown in Chapter 2.

Considering the "Smartification" and the "Selection" procedure, the "Magic Smartifier" needs this components:

- RFID Reader
- Accelerometer Board (developed to the Micrel Lab)
- CPU

- Wireless Connection, *i.e.* Wi-Fi communication
- Functionality Selector
- User Feedback, *i.e.* LEDs and vibro-tactile motors.

If this characteristics are compared with the Smart Object list of properties (Chapter 3), it can be derived that the “Magic Smartifier” is a Smart Object.

The Verdex Pro Gumstix CPU has been chosen for the development. This board contains also wireless functionality.

To perform the “Smartification” and the “Selection” and every Smart Environment management tasks, the Smart Object has to communicate with the Smart Space in a defined way. To do this, considering the *digital* Smart Environment structure seen in Chapter 2, every active object which communicate with the Smart Space must be linked to a *Knowledge Processor* (KP). This KP formats the data in a manner understandable by the Smart Space and this data are sent to the Smart Space utilizing the Wireless Communication. In the case of the “Magic Smartifier”, the Functionality Selector choses one of the two possible tasks, and two KPs are implemented within the onboard CPU.

The block diagram of the Smart Object is shown in .

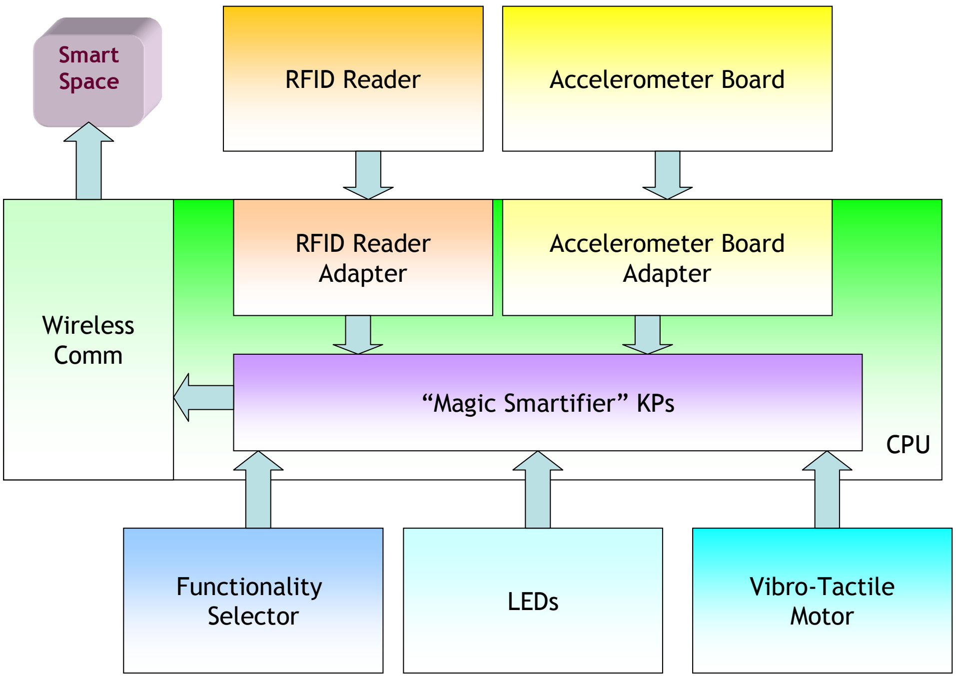


Fig. 4. 1 “Magic Smartifier” Block Diagram

The RFID and the Accelerometer Board Adapters handle the communication between the RFID and Accelerometer Board and the KP, *e.g.* they handle the serial communication and the interrogation from the devices and the CPU.

The LEDs and the Vibro-tactile motor can be used to accomplish the Feedback for the user, according to the Natural Interaction principles see in Chapter 3.

In our implementation only two procedure are performed utilizing the "Magic Smartifier". Other are possible, increasing the KP functionalities and the possible selections, as for example:

- semantic connections between an active physical object and the SO: the SO is used like a remote control to control one or more physical object's actuators
- semantic connections between two active physical objects: the SO is used for diverting the flow of data from an object to the other.

4.1.1 Interaction Methods

As seen, the "Magic Smartifier" can be used for different tasks, selected by the Functionality Selector. LEDs and Vibro-Tactile Motor give feedback to the user about what is happening in the selected mode. For each use of the SO User Interaction methods can be defined. User Interaction methods are a sequence of actions by which the user communicate with the Smart Space, the SO and the environment. This sequence of actions are translated within the SO as a series of the following micro-actions:

- communication between the RFID Reader Adapter or Accelerometer Board Adapter, and the SO KP
- communication between SO KP and the Smart Space.

The two procedures which can be performed utilizing the "Magic Smartifier" implie some hypothesis:

- the composition of the environment is known as is the relationship with its mapping in space (as seen in Chapter 2)
- the Identification of the environment components are known
- the association between a *gesture* and the corresponding *action* is known (also by the user)

In the following Interaction Procedures, this notation is used:

- the environment components, *e.g.* the RoomA, has its Identification called *ID_A*
- the object ObjectB has its Identification called *ID_B*
- the desired *action* correspondent to the *gesture* is called *Action_C*

Regarding the "Smartification" if the user wants to "Smartify" the ObjectB inside the RoomA, the User Interaction Procedure can be this:

1. the user reads *ID_A* pointing the "Magic Smartifier" to the room identifier
2. the "Magic Smartifier" asks to the Smart Space information about *ID_A*
3. the Smart Space give information about *ID_A*
4. the "Magic Smartifier" gives a Feedback to the user

5. the user reads *ID_B* pointing the “Magic Smartifier” to the object identifier
6. the “Magic Smartifier” asks to the Smart Space information about *ID_B*
7. the Smart Space give information about *ID_B*
8. the “Magic Smartifier” gives a Feedback to the user
9. the “Magic Smartifier” sends to the Smart Object the information that (*ID_A contains ID_B*)
10. the “Magic Smartifier” gives a Feedback to the user

The steps 2., 6. and 9. requires communication with the Smart Space. After step 10. the *digital* copy of ObjectB is present in the Smart Space. The temporal diagram of the “Smartification” is shown in Fig. 4. 2.

Regarding the “Selection” if the user wants to associate to ObjectB the *Action_C*, the User Interaction Procedure can be this:

1. the user reads *ID_B* pointing the “Magic Smartifier” to the object identifier
2. the “Magic Smartifier” asks to the Smart Space information about *ID_B*
3. the Smart Space give information about *ID_B*
4. the “Magic Smartifier” gives a Feedback to the user
5. the user perform a gesture which is associated to the *Action_C*
6. the “Magic Smartifier” sends to the Smart Space the information that (*Action_C isRelativeTo ID_B*)
7. the “Magic Smartifier” gives a Feedback to the user

The steps 2. and 6. require communication with the Smart Space. After step 7. the *digital* copy in the Smart Space of ObjectB is associated with an action which value is *Action_C*. The temporal diagram of the “Selection” is shown in Fig. 4. 3.

4.2 Design Of Power Supply Sub-System For Smart Object

One of the Smart Object blocks is the power supply one. These are not indicated in the above block diagram. This Paragraph intend to present an approach to the design of power supply sub–system for Smart Object (called in this work *SOPM*s Smart Object Power Manager). Their design takes into consideration that the Smart Objects must be portable and wireless. As seen in the previous sections, the Smart Object components are widely non homogeneous: sensors, actuators, CPU, wireless interface. For this reason during the doctoral work SOPM design was divided in different power band, depending on Smart Object computational capacity and communication. This is also dictated by the need to avoid wastage of resources and make the whole system as miniaturized as possible.

For the moment we have identified two band of use, depending on the maximum load power:

- Band 1: maximum load power 400 mW
- Band 2: maximum load power 4,5 W

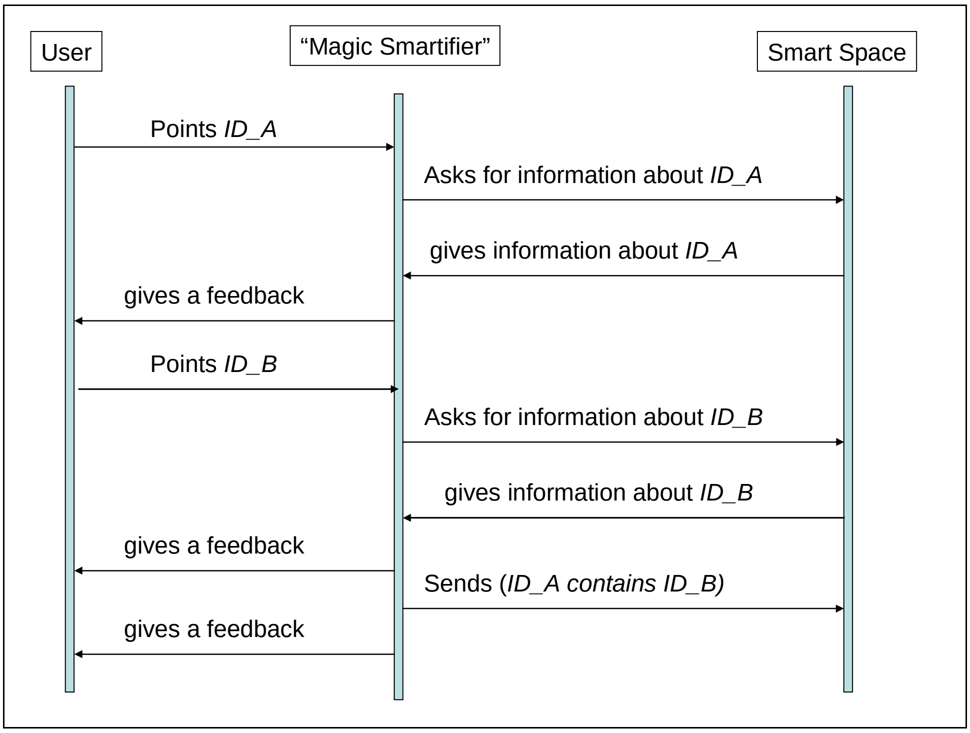


Fig. 4. 2 “Smartification” Temporal Diagram

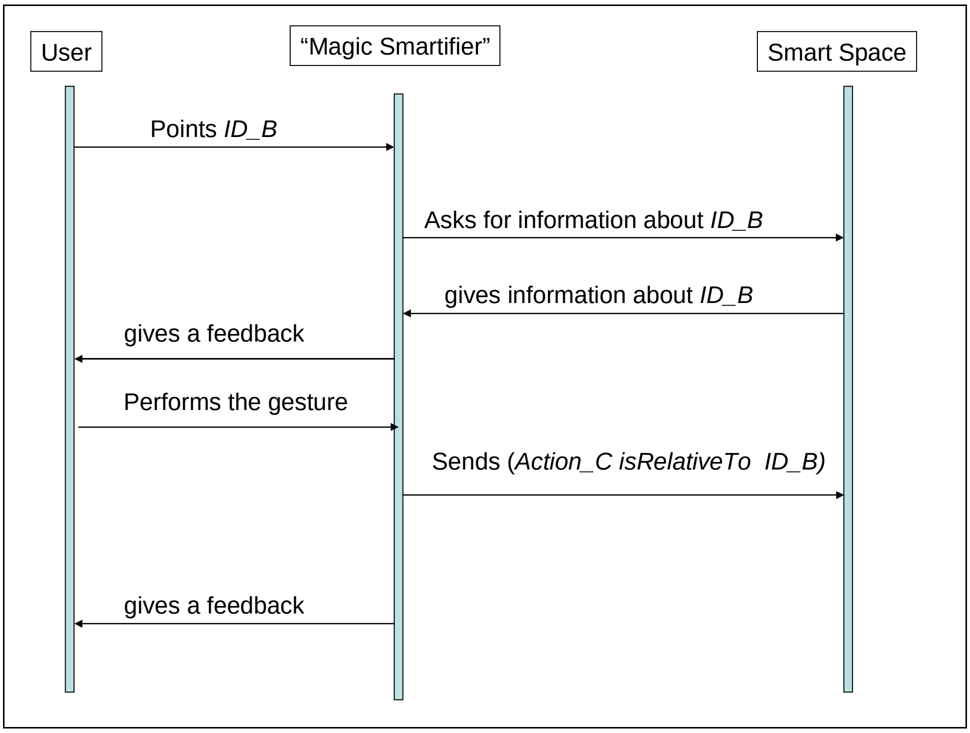


Fig. 4. 3 “Selection” Temporal Diagram

During the doctoral work were found the parameters which discriminate the design of SOPM. These (not mutually exclusive with each other) are:

- battery type: number of cells, maximum capacity, maximum discharge current;
- power supply unit type: typology (linear o switching), efficiency, output continuous current, output voltage;
- battery charger type: charging methodology, battery protection methodology
- relationship between the battery working voltage and the SO voltage.

After an overview of the choices taken into consideration related to the above points, the Paragraph describes the design and the results of a Band 1 SOPM. In addition, to complement the discussion on SOPM, it shows the general schema of a possible implementation of a Band 2 SOPM.

4.2.1 Design Principles of Band 1 SOPM

As mentioned previously the choice of supply sub–system for Smart Object Band depends on the power characteristics of the load, which in turn depends on the computational and communication properties of SO.

Considering the Band 1 (which is identified with a maximum power load of 400 mW) the characteristics of a potential load can be summarized as in Table 4. 1.

CPU type	MSP430
Operating system presence	No
Extern Communication mechanisms ▪ wired ▪ wireless	 ▪ USB ▪ Bluetooth
Sensor Type	Inertial Sensors Magnetic Sensors
User Interface Type	ON/OFF switch Two LEDs

Table 4. 1

Considering a load of this type, Fig. 4. 4 indicate the power consumption of the load in the most significant operational conditions:

- Bluetooth Discovery phase, when all the sensors are turned on

- USB communication when the Bluetooth module is tuned off and all the sensors are turned on

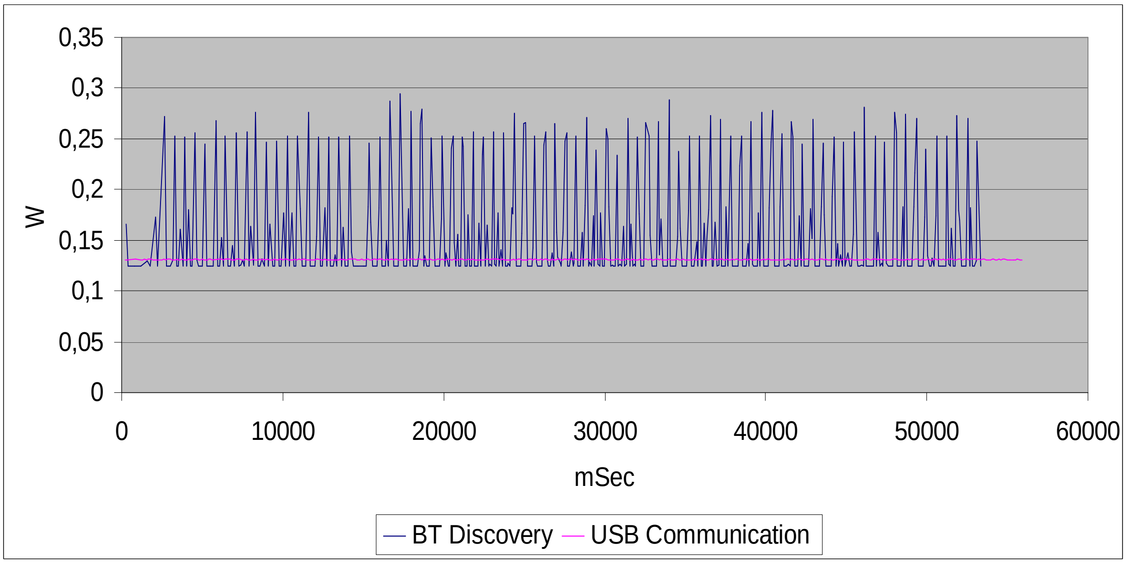


Fig. 4. 4 Possible Band 1 Load power consumption

As can be seen in Fig. 4. 4, the maximum power consumption conditions (300mW of peak), occurs during the Bluetooth discovery phase, *i.e.* the phase of searching for other radio modules by the BT module.

Another feature that would be important for the loads of Band 1 SOPM, is the power independence of parts of the circuit achieved utilizing linear regulators with low Drop-Out. In this way, loads would be able to:

- Convert the output voltage of the SOPM from the output voltage of the load (small difference between the two voltages)
- Turn on and off parts of the circuit

In Fig. 4. 5 is illustrated the Band 1 SOPM and its possible load. This meets the following requirements:

- The subsystem should be battery powered
- The subsystem should operate independently for at least 8 hours
- The battery should be integrated into the subsystem SOPM
- The subsystem should have 3.6 V of output voltage, with a ripple of less than 10 mV
- The subsystem should be as efficient as possible

In the development of SOPM module, the choice of the battery type and of the battery characteristics, influence the entire design process. Important constraints to consider when selecting the battery are:

- capacity

- voltage operative range
- maximum discharge current
- protection circuits

For the best choice of the battery, the following parameters have to been taken into considerations:

- charging method
- capacity – volume ratio
- number of charging/discharching cycles
- performance.

Among the several battery types considered, Lithium–Ion or Lithium–Polymer (same charging/discharching characteristics, but lighter and less dangerous) batteries, score higher in all the features above.

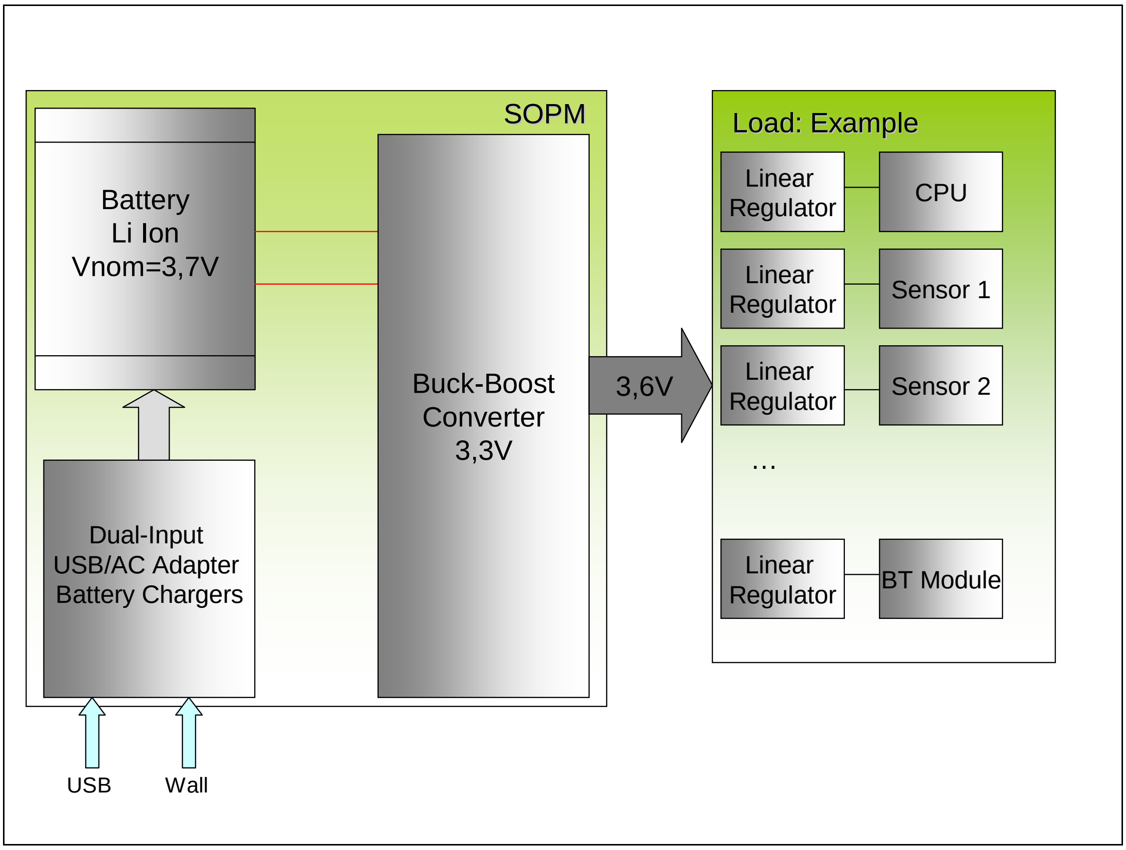


Fig. 4. 5 Band 1 SOPM and its possible load

In the Table 4. 2 it is reported the necessary characteristics of the battery and the relative selection criteria.

Battery Characteristics	Selection Criteria
1 Series Cell (1S)	Size and weight
2 Parallel Cells (2P)	Soft–start in–rush current of 2500mA
Battery - Pack (protection circuits on the battery: over–current, over–voltage e under–voltage)	Avoid damaging the battery
Temperature sensor on the battery	Flammable protection

Table 4. 2

This guide lines are further illustrated in a case study in Appendix D.

After reporting the schema of a subsystem SOPM Band 1 is interesting now to dwell on the design and generalization of a Band 2 SOPM. This Band of operation is identified by a maximum power load of 4.5 W. The characteristics of a possible Band 2 load are listed in Table 4. 3.

CPU type	Computer on module Gumstix Verdex Pro XM4-bt
Operating system presence	Yes (linux)
Extern Communication mechanisms ▪ wired ▪ wireless	▪ USB Ethernet ▪ Bluetooth WiFi
Sensor Type	Inertial Sensors RFID Reade
User Interface Type	ON/OFF switch Functionality switch Two LEDs Vibro–Tactile motor

Table 4. 3

Considering this load typology, in Fig. 4. 6 are reported the load power consumption in two significant operational condition:

- CPU and Wi–Fi boot
- Normal operation (Wi-Fi activated)

As it can be seen, the maximum power consumption is about the 4W.

In respect to these data, it can be hypothesised a general schema for a Band 2 SOPM. Fig. 4. 7 reports a conceptual design, according to the general methodology explained above.

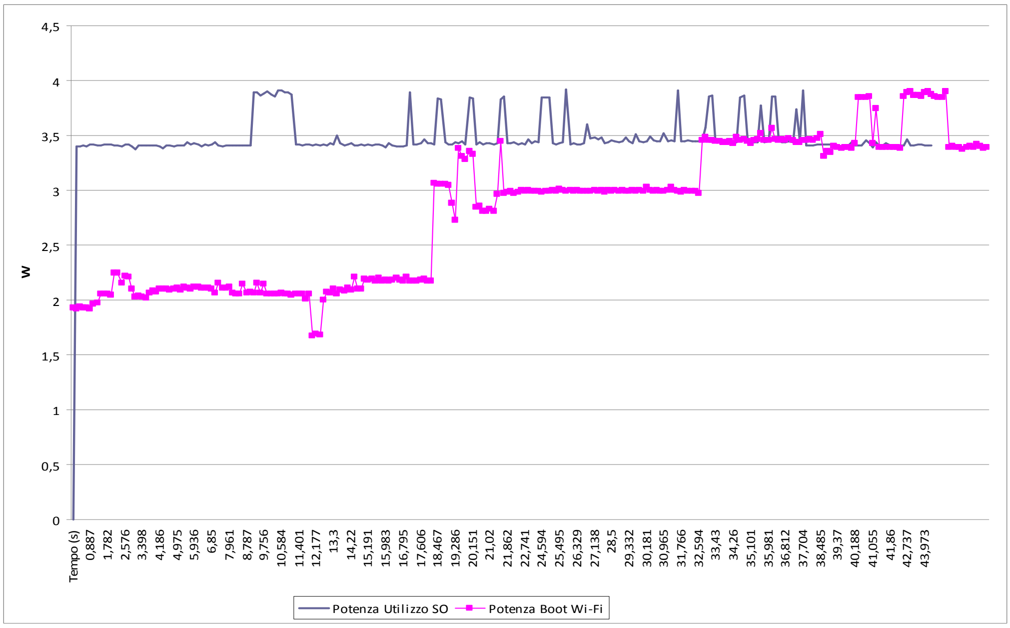


Fig. 4. 6 Typical Band 2 load power consumption

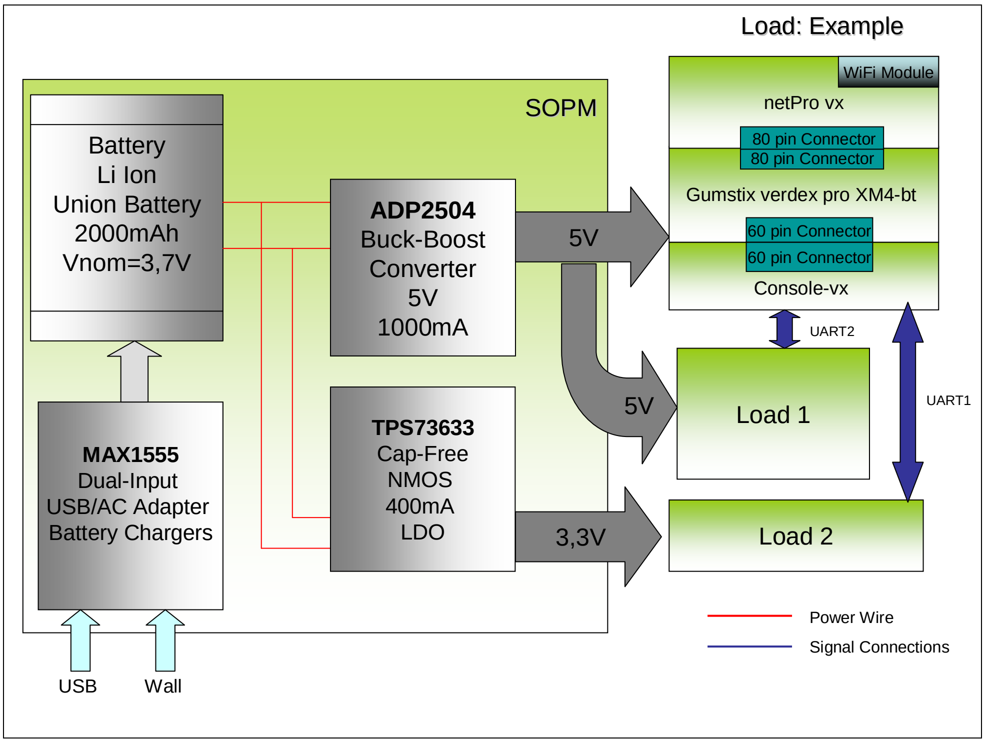


Fig. 4. 7 Possible Band 2 SOPM implementation

Part II

SMART SENSORS FOR LOCATION ESTIMATION

Chapter 5

PEDESTRIAN POSITIONING SYSTEMS

In this Chapter is presented an overview on Pedestrian Positioning Systems.

There are several research and industrial groups which work in the wide panorama of Positioning Systems for tracking the position of people, vehicles and objects. For outdoor open sky environments, the GPS represents for sure the well know and adopted solution to track people and vehicles. In unconstrained environments, *i.e.* indoor-outdoor, the lack (or the weakness) of the GPS signal imposes to adopt other solutions, mainly based on the integration of different technologies, like for example Inertial Systems, Wi-Fi, Bluetooth, Zigbee, WiMax and RFID.

The aim of this Chapter is to give a justification to the work developed in the PhD period regarding the Navigation Systems, and to give an excursus of the other works present in this research area.

In Paragraph 5.1 an overview of the tracking technologies is introduced. In Paragraph 5.2 is introduced the problem of the user positioning, in particular the Dead Reckoning techniques and the algorithms to detect the length of human steps are highlighted. The choices of the user positioning method, made on in this PhD work, are stressed. In Paragraph 5.3 Multi-Sensor Approach to perform the Pedestrian Navigation system is introduced and several Multi-Sensor platform are compared.

A definition on some requirements necessary to give an indication of the Pedestrian Navigation Systems qualities are indicated in this Paragraph 5.4.

5.1 Pedestrian Tracking Technologies

Starting from old time coastal navigation, people had the necessity to localize themselves, other people or vehicles. Nowadays, several technologies and methods are utilized to localize people and vehicles, also in some combinations. The integration of different technologies is essential to guarantee the reliability of the position information. An important branch of navigation systems is focused on localizing users traveling on foot. This type of systems are called Pedestrian Localization Systems (PNS) or Tracking Systems, intending with this the process of determining and maintaining positional information for a person traveling on foot.

First of all, it is important to clarify what kind of information a PNS can provide. A PNS system has to give the position of a user. The position information can be used into Location Based Services (LBS) utilizing for example Geographic Information System (GIS) or maps. These have the purpose to represent the space with the granularity needed in the specific application, (*e.g.* a user is in a building, a user is in a floor, a user is in a room). In other words, they give to the position data a *meaning* in a reference system, extrapolatig the location. (Filjart, 2008) suggests a definition for the two terms: *position* and *location*. For *position* is intended the place of a physical object in a given spatial co-ordinate system. One of the most common means of expressing position, in terms of navigation, is the combination of latitude, longitude and height above the sea level. The *location* is a position enriched with additional information elements, referring to the relationship between the physical object (represented with its *position*) and the surrounding area.

There are several works which provide a classification of different positioning systems and technologies. In (Retscher, 2006b), an overview of newly developed ubiquitous position technologies and their integration in navigation system is proposed. (Pettinari, 2007) suggests a classification of the more relevant positioning technologies, based on the distinction between Dead Reckoning and non-Dead Reckoning approach. (Gerónimo, 2009) presents a novel strategy to survey the different approaches to detect user presence starting from pedestrian tracking based on cameras. It divides the problem to detect pedestrian into different steps and it analyzes and classifies them with respect to each processing stage. In the report proposed by (Chan, 2005) is provided a summary of a literature review analysis on various pedestrian technologies and technical approach.

In Table 5. 1 (Retscher, 2006b) are compared some possible position techniques comparing their accuracy. In Table 5. 1 are also reported the observables: x, y and z are the 3-D coordinates of the position, v_x, v_y and v_z are the 3-D velocities, a_x, a_y and a_z are the 3-D accelerations, a_{tan} is the tangential acceleration, a_{rad} is the radial acceleration in the ground plane, χ is the direction of movement (heading), Φ and Θ are the Inclination (Tilt) Angles (Roll and Pitch).

Positioning Method	Observables	Accuracy
GNSS GPS DGPS	*x*, *y*, *z*	 ±6-10 m ±1-4 m
Velocity from GNSS	v_x, v_y v_z	±0.05 m^{-1} ±0.2 m^{-1}
Cellular Phone (GSM) Cell-ID Matrix	*x*, *y*	 ±150 m-35 km ±50 m-100 m
WLAN	*x*, *y*, *z*	±1-3 m
UWB (TDOA)	*x*, *y*, *z*	±0.1-1 m
RFID (active tags+point-of interests)	*x*, *y*, *z*	±6 m
Bluetooth(point-of interests)	*x*, *y*, *z*	±10 m
Inertial Navigation Systems	a_x, a_y, a_z Φ, Θ, χ	<±0.08 ms^{-2} <±0.03 °/s
Dead Reckoning Systems	*x*, *y* *z* χ	±20-50 m per 1 km ±3 m ±1°
Heading	χ	±0.5°
Acceleration	a_z, a_{tan}, a_{rad}	>0.03 ms^{-2}
Barometer	*z*	±1-3 m

Table 5. 1 (Retscher, 2006b)

Recently, several positioning technologies have been developed in Navigation Systems. Everyone can be utilized in specific applications and environments, depending on the technology characteristics. In this Paragraph is presented an overview of this technologies, including also those for the motion tracking (Welch, 2002). The technologies are subdivided in two ways: in respect to the environment in which are applied and in respect to the need of additive infrastructures in the environment or worn by the user. In the latter, technologies can be divided in those which work only outdoor, those which work only indoor and those which work both outdoor and indoor (Table 5. 2). In the former distinction, they can be divided in those which work without adding infrastructure in the environment and on the user, or those which work adding infrastructure in the environment and on the user (Table 5. 3)

Outdoor Technologies	GPS
Outdoor and Indoor Technologies	Cellular Networks
	Radio Frequency
	Mechanical
	Optical
	Ultrasound
	Vision
	Magnetic
	Inertial and Heading

Table 5. 2

No Infrastructure-needed Technologies	GPS	
Infrastructure-needed Technologies		**Type of Infrastructure needed**
	Cellular Networks	Mobile Phone or Smart Phone
	Radio Frequency	Access Points WiFi module
	Mechanical	Mechanical structure
	Optical	Light source Marker
	Ultrasound	Ultrasound source Marker
	Vision	Camera
	Magnetic	Magnetic component
	Inertial and Heading	Initial position

Table 5. 3

5.1.1 GPS Technologies

The most popular navigation system is the Global Positioning System (Dana, 2000). It provides services to unlimited users by transmitting a signal which comprises the satellite identification code, the time stamp and the position information. The position of a physical object which wears a GPS receiver, is performed by means of a triangulation based on the Time-Of-Arrival information. A user needs a minimum of four satellites in view to estimate his four-dimensional position: three coordinates of spatial position, plus time. For this reason, several problems afflict GPS technology particularly in urban geographic environments where no signals can be received. The GPS is an example of positioning technology which works only outdoor and no additive infrastructure are needed.

To decrease the problems occurring in the GPS positioning, many techniques have been studied: the Differential GPS (DGPS) (Monteiro, 2005), is a method used to increase integrity and accuracy by using land-based reference station which computes the error; the Assisted GPS (A-GPS) (Jarvinen, 2002), is used to overcome the delay problems, accelerating the process of position determination and reducing it to only a few seconds, with the minimum impact on the network infrastructure; the Satellite Based Augmentation Systems (SBAS) (U.S.D.T., 2001), support a satellite differential correction, whereby the correction signals that improve the accuracy of the GPS receivers are transmitted by satellite; the Real-time Kinematic (RTK) is based on the analysis of the carrier phase of GPS satellite signals rather than the usual pseudorandom signal; the High-Sensitive GPS (HSGPS) can also works indoor and are capable of tracking signals that are 20-30 dB weaker than the typical outdoor signal. However, concerning this last case, in (Lachapelle, 2004) are presented some results on indoor positioning. The position accuracy is lower than the case of open space. Also in (Hide, 2006), this fact is demonstrated. In fact, the combination of a DGPS and Inertial System can provide horizontal positioning accuracy of 2.5 m RMS, instead of an horizontal positioning accuracy of 5 m RMS utilizing the HSGPS.

(Abowd, 1997) presents the Cyberguide project, in which they were building prototypes of a mobile context-aware tour guide. While indoor positioning relies on infrared beacons, the outdoor positioning is provided by GPS receiver connected to an handheld device. A PDA guide that uses GPS signal is Arianna (Foresti, 2006).

In (Kim, 2008) is presented a method for localizing and reconstructing a urban scene using GPS.

Currently, the GPS is integrated with other positioning systems (as it will be seen in the Paragraph 5.1.1.10).

5.1.2 Cellular Network Technologies

The position determination of cellular phones or mobile devices is developed using the signal of the cellular network. The achievable positioning accuracy depends manly on the position method and on the type of cellular network (GSM, W-CDMA, UMTS). Most of the positioning method based on cellular network are based on observations of two base transmitting stations to provide a 2-D position (Hein, 2000). This is an example of position method which work both indoor and outdoor. Only a mobile phone is needed with the user, the additive infrastructure in the environment is not needed.

The GSM positioning (Drane, 1998; Otsason, 2005) is particularly employed. Different techniques can be used to determine user position through GSM technology. If compared to other positioning technologies, like for instance the Wi-Fi one, GSM is not subjected to interference, works in critical power conditions, and provides a network coverage greater than those provided by Wi-Fi networks. The use of Cell-Id is one of the simpler way to localize a mobile phone (Zhao, 2002). This approach provides only a positioning accuracy between 150 m and 1 km in urban areas, and up of 34 km in rural areas. To overcome this limitation in addition to the cellular network are utilized: database correlation method (Laitinent, 2001), indoor positioning (Otsason, 2005) or outdoor positioning (Chen, 2006).

Recent developments have concentrated on the reduction of network modification for advanced positioning. The Matrix method (Duffett-Smith, 2004) is based on the Enhanced Observed Time Difference without any other additional hardware apart from a Servicing Mobile Location Centre where the location determination is performed.

Regarding the UMTS network, the network includes the support of location services (Balbach, 2000). Similar position determination techniques as with GSM network can be applied. But in addition, timing measurements at the terminal are added (Borkowski, 2006).

5.1.3 Radio Frequency Technologies

Positioning methods based on Radio Frequency are based on temporal information or signal attenuation. The most important radio localization systems are Wireless LAN, Bluetooth, Zigbee and UWB. The Radio Frequency technologies can be utilized both indoor and outdoor and there is the need of additive infrastructure installed in the environment and with the user.

The Wireless LAN positioning has become popular in recent year. The WLAN network consists of fixed access point and mobile devices equipped with wireless hardware. The position determination is performed by measuring the signal strength of the radio signals from at least one access point. The position is obtained with triangulation of measurements of different access points (Xiang, 2004) or through fingerprinting where the measured signal strength values are compared with a database storing the signal values (Bahl, 2000; Beal, 2003). As the indoor radio channel suffers from multi-path propagation, the fingerprint method achieved higher positioning accuracy than triangulation.

The Ultra Wide Band Systems positioning relies on a good multi-path resolution (Win, 1998). UWB can be employed for measuring accurate Time of Arrival (Lee, 2002) or Time Difference of Arrival (Kong, 2004) for estimating the distance. In (Pahlavan, 2002) is presented an overview of the technical aspects for wireless indoor positioning systems based on UWB.

Radio Frequency Identification (RFID) is employed in the applications which need contact-less transmission of product information. Different positioning method are proposed depending on the type of RFID which are used: frequency range, visibility distance, passive or active tags. To employ RFID to perform vehicle positioning, the most simple approach would be to install RFID tags along road and have the reader and the antenna in vehicle (Chon, 2004). The same thing can be performed in indoor space for people. The tags are installed for example in corridors or room and the reader and antenna are with the user (for example utilizing an handheld device provides of reader and antenna). Another possible application would be to install tags at specific points-of-interests and if the user passes near one of this, his or her position is updated (Hsi, 2004).

In (Ni, 2005) the proposed LANDMARC application is based on active RFID tags. This improves the accuracy in locating objects utilizing reference tags. These tag are at fixed position and are used to help the mobile reader positioning by means of a received signal strength. The same idea is proposed in (Hightower, 2000), where multiple base stations provide signal strength measurements mapping to an approximate distance. The Ferret system (Liu, 2006) is implemented to locating nomadic objects augmented with RFID tags.

The Zigbee technology is an emerging standard based on the IEEE 802.15.4. The main advantage over other positioning systems is that ZigBee transceivers are low powered, small and inexpensive. Not many positioning works based on ZigBee have been developed. A position estimation system utilizing a wireless sensor network based on the ZigBee standard is implemented in (Sugano, 2006). The system automatically estimates the distance between sensor nodes by measuring the RSSI (received signal strength indicator) at an appropriate number of sensor nodes. A novel algorithm based on a Zigbee sensor network called Ecolocation is presented in (Yedavalli, 2005). This algorithm determines the position of unknown nodes by examining the ordered sequence of received signal strength (RSS) measurements taken at multiple reference nodes.

Also Bluetooth, can be employed for locating user and mobile devices in applications which need an in-sight distance of less 10 meter. For this reason Bluetooth technology is not particularly used for positioning. Some examples of indoor localization will be given. (Rodriguez, 2005) who presents an indoor localization system based on Bluetooth access points. Positioning is made by means of the signal strength received from those access points. The signal energy will be measured by a mobile device and it will be transmitted to a central server that calculates its location. This system is similar to the RADAR ones. (Kotanen, 2003) presents a design and an implementation of the Bluetooth local positioning application based on received power levels, which are converted to distance estimates according to a simple propagation model. An experimental evaluation of a Bluetooth-based positioning system implemented in an handheld device is developed in (Feldmann, 2003). The range estimation of the positioning system is based on an approximation of the relation between the RSSI and the associated distance between sender and receiver. The actual position estimation is carried out by using the triangulation method. (King, 2009) demonstrates that Bluetooth nowadays provides adequate mechanisms for positioning in an office environment. The paper proposes a Bluetooth-based positioning system and shows by means of emulation with real-world data that a positioning accuracy of about 2.5 meters is achievable.

The iPLOT intelligent pervasive position tracking system is exposed in (Mautz, 2006). The system is an automatic, low-cost system that exploits current or near future wireless communication based on Bluetooth signals to enable tracking of the position of devices in all environments. In this system radio enabled devices are located within ad-hoc networks of static and mobile users and equipments. This nodes have functionality to connect themselves to the network automatically.

5.1.4 Mechanical Technologies

Mechanical Trackers are based on rigid or flexible structures which are worn by the user. This structures have to measure positions of links. This link are related each other by means of a skeleton. The angles links are calculated to provide the kinematic model of the motion. This approach can provide very precise and accurate pose estimates for a single target, but only over a relatively small range of motion. This technology can be utilized both indoor and outdoor and there is the need of additive infrastructure installed in the environment and with the user.

Due to variations in anthropomorphic measurements, body-based systems must be recalibrated for each user. In his pioneering work (Sutherland, 1968) built a mechanical tracker composed of a telescoping section with a universal joint at either end.

An innovative mechanical tracker is proposed in (Tarri, 2009). The new device has a modular structure that exploits three mechanical units each composed of two rotational joints and allows to scale the usable workspace by substituting the connecting links. The sensing principle for the joint angles measurement is based on an innovative hall-effect angle sensor with high resolution, developed and conceived for low cost applications.

A discussion of general issues which must be considered in evaluating human movement tracking systems and a summary of currently available sensing technologies for tracking human movement are proposed in (Mulder, 1994).

An industrial mechanical tracking system is the GYPS (Dickson, 1999) developed by MetaMotion. In this system the sensors and the signal sources are on the mechanical support worn by the user. The signal is then transmitted by Radio Frequency.

5.1.5 Optical Technologies

The optical tracking is performed through devices which are equipped of sensors of light, infrared or laser. They are characterized by non-interference with other electronics devices, even if they suffer from interference from ambient light and from other IR devices in the environment. There are two different typologies of optical systems: those which utilizes the light of the environments (passive or reflective), and those which produces luminous signals (attive, *e.g.* LED, LASER…). In the category of marking optical systems three principal technologies are present:

- marker detection: cameras are the sensing elements which detects colored markers (LED or colored points) applied on object or user. This method is accurate and less intrusive, but are sensible to reflections and lighting variations
- LASER-radar: they measures, such as acoustic systems, the Time-Of-Flight of a LASER beam punting an object. This method are accurate and small, but they have less resolution and high price.
- Infrared: they have the same functioning of the marker detection. The cameras are equipped by infrared vision, and the marker are reflective. This are small and not necessitate of a calibration. They are expensive and sensitive to reflection.

All this methods can be utilized both indoor and outdoor and there is the need of additive infrastructure installed in the environment and on the user.

A system for locating people in an office environment based on IR technologies is proposed in (Want, 1992). Each person the system can locate wears a small IR badge that emits a globally unique identifier. A central server collects this data from fixed IR sensors around the building, aggregates it, and provides an application programming interface for using the data. A badge's position is symbolic, representing, for example, the room in which the badge is located. A nomadic guide on a mobile devices which sense IR beacon installed near a point of interest is developed in (Oppermann, 2000). An approach of integration between optical system and Inertial System is exposed in (Roetenberg, 2006).

A novel system for tracking pedestrians in a wide and open area, such as a shopping mall and exhibition hall, using a number of single-row laser-range scanners (LD-A) is proposed in (Zhao, 2005). LD-As are set directly on the floor doing horizontal scanning so that horizontal cross sections of the surroundings, containing moving feet of pedestrians as well as still objects, are obtained in a rectangular coordinate system of real dimension. The data of moving feet are extracted through background subtraction.

From the industrial point of view, the IS-1200 developed by the Intersense (Intersense, 2009), is an hybrid technology. It integrates Inertial Sensors and Optical technology based on marker detection.

5.1.6 Ultrasound Technologies

Find the position of a user (or object) utilizing Ultrasound technology means using a transmitter and a receiver. The distance between the two is computed utilizing the Time-Of-Flight of the Ultrasound beam. Six degree of freedom are obtained by means of more sound source and computing triangulation (Rolland, 2001). These systems are low cost, are small, and can be utilized for high distance. But They are sensitive to interference and they have high latency.

This technology can be utilized both indoor and outdoor and there is the need of additive infrastructure installed in the environment and with the user.

A type of positioning method of pedestrian user by means of Ultrasound, is presented in (Harter, 2002). The mobile phone user is followed around the building because carries a tag equipped by an Ultrasound transceiver. Fixed position tags are positioned on the ceiling. The user position is calculated by means of triangulation between the user tag and the nearest fixed tags.

The design, implementation, and evaluation of a location-support system for in-building, mobile, location-dependent applications, named Cricket, is proposed in (Priyantha, 2000). It allows applications running on mobile and static nodes to learn their physical position by using listeners that hear and analyze information from beacons spread throughout the building. Cricket implements both the triangulation and proximity techniques and uses a combination of Radio Frequency and Ultrasound technologies to provide position information to attached host devices.

The IS-900 developed by Intersense (Intersense, 2009), is an hybrid tracking system. It utilizes Inertial Sensors and Ultrasound sensors. The drift error due to the Inertial sensor is corrected with a Kalman filter which utilizes the Ultrasound data.

5.1.7 Vision Technologies

For Vision positioning is intended the localization of users (or objects) by means of camera. There are several tracking method which utilizes the vision technologies. (Yilmaz, 2006) reviews the state-of-the-art tracking methods, classifies them into different categories and identifies new trends. All the tracking methods based on vision can be utilized both indoor and outdoor and there is the need of additive infrastructure installed in the environment and on the user.

Two different approaches can be used to detect user’s position: cameras in the building or cameras on the user. In the former, the building can be equipped with cameras, which detect the moving objects. The latter consists in mobile user equipped with a small camera. Visual tags are attached on walls inside the building. In this case, the visual tags have fixed positions. If the mobile camera detects two or more tags, it can find out its own position.

(Gavrila, 2004) presents the results of a large scale field tests on vision based pedestrian protection from a moving vehicle. The system is called PROTECTOR and combines pedestrian detection, trajectory estimation, risk assessment and driver warning. The implementation of a vision-based system for recognizing pedestrians in different environments and locating them with the use of a Kalman filter is shown in (Bertozzi, 2004b). An improvement of this system is proposed in (Bertozzi, 2004a) where pedestrian detection is performed with infrared cameras.

Stereo-Vision systems improve the vision systems, in order to achieve higher grades of robustness (Salmon, 2006).

5.1.8 Magnetic Technologies

The tracking systems based on magnetic sensors represent a good example of *inside-out* systems (Rolland, 2001), in which the sensors are placed to the mobile target and sense only an external source. The sensor placed on the object measures magnetic fields generated by a transmitter source. To measure position and orientation of a receiver in space, the emitter must be composed of three coils placed perpendicular to each other, thus defining a spatial referential system from which a magnetic field can exit in any direction. The direction is given by the resultant of three elementary orthogonal directions. On the receiver, three sensors measure the components of the field's flux received as a consequence of magnetic coupling. Based on these measures, the system determines the position and orientation of the receiver with respect to the emitter attached to the reference. Taking into account the above explanation, this technology can be utilized both indoor and outdoor and there is the need of additive infrastructure installed in the environment and on the user.

One of the first work based on the magnetic tracking is (Raab, 1979), in which the technology is exposed and designed. A novel approach of integration between magnetic tracker and Inertial System is exposed in (Roetenberg, 2006).

An industrial interesting magnetic system is Flock of birds (Ascension, 2009), developed by Ascension. The system permits to follow four sensors at the same time. It is utilized in many application, such as simulation and virtual reality. Different from the Flock of birds system, the Liberty's Polhemus product (Polhemus, 1969) is based on alternative current.

5.1.9 Inertial and Heading Technologies

Inertial sensor are the components of Inertial Navigation Systems (INS). These are based on accelerometers and gyroscopes. The accelerometer measures the acceleration of the mass on movement and the gyroscopes the angular velocity of rotation mass. The low level data are then the accelerations and the angular velocity (for details see Paragraph 6.2).

By means of the angular velocites and accelerations it is possible to calculate the orientation of an object in the space and eventually its position and velocity. The systems that calculate this orientation are called Heading systems where for Heading is intended the direction of movement.

The direction of a moving object (or in general its orientation), and its position can be calculated utilizing the Dead Reckoning (as it will be seen in Paragraph 5.2.1), theoretically without the use of external infrastructure during the walking. In practical the position is calculated referring to the inertial reference frame, that is the reference system of the gyroscope. If the INS has to be integrated in a system which provides information of the position of the user in a specific reference system (such as the Geographic reference system), the initial position and orientation have to be imposed. Several method to impose initial position and orientation exist. In (Jamshaid, 2005), a list of these method is proposed. Practically, the alignment can be derived from another source, such as human operator, GPS, RFID tag (Torres, 2007; Salmon, 2008), heading magnetic sensors, or Cameras (Salmon, 2007).

As seen, the Inertial Navigation Systems, are practically based on gyroscopes. The main sources of error of the gyroscopes will be exposed in Paragraph 6.1 (Woodman, 2007). Briefly, the most important sources of errors for MEMS gyroscopes are uncompensated temperature fluctuations or an error in the initial bias estimation. This errors are called *Angle Random Walk* (or *Integration Drift*) because cause the equivalent of an angle rotation. In fact, it is produced in the integration of the above mentioned error sources, when the angular velocity is integrated to compute the angular rotation.

To diminish these error a proposed approach is the *sensors fusing* in which the information derived from different sensors are integrated. The idea behind fusing of different sensors is that characteristics of one type of sensors are used to overcome the limitations of other sensors. For example magnetic sensors are used as a reference to prevent the gyroscope integration drift (Kappi, 2001). A similar approach will be analyzed in the Paragraph 6.4. On the other hand, the information derived from a gyroscope not affected to the integrated drift can be utilized to prevents errors in the orientation in respects to the magnetic North, due to magnetic disturbances in Heading system based on magnetic sensors (Ladetto, 2002a).

The more convenient method to perform the sensor fusing is utilizing the Kalman Filter where a dynamic or kinematic model of the sensors is necessary (Parkinson, 1996; Brown, 1997b; Farrel, 1999; Grewal, 2001).

In (Carlson, 1988) an efficient Kalman filtering method is presented, based on rigorous information-sharing principles. This method provides globally optimal or near-optimal estimation accuracy, with an high degree of fault tolerance. The local filter outputs are presumed to be independent.

(Torres, 2007) utilizes a Kalman filter to integrate data deriving from accelerometer, gyroscope and magnetometer to realize a wearable miniaturized inertial measurement unit. (Ladetto, 2002a) developed a system in which the Heading is computed utilizing a digital compass, and gyroscopes and a Kalman filter are used to compensate the heading calculation when magnetic field is disturbed to magnetic interferences.

Adaptative Kalman filters prevents divergence problem present in the Kalman filter when precise knowledge on the system models is not available. Two popular types of adaptative Kalman filter are: the Innovation Based Adaptative Estimation (IAE) and the Adaptative Fading Kalman Filter (AFKF). In (Jwo, 2008) is proposed a synergy of the two methods.

In (Yang, 2004), is proposed an adaptatively robust filtering approach was developed and shown to be effective for controlling the bad influences of the measurement outliners and the disturbances of the dynamical model on the estimated state.

In (Cho, 2006) the Pedestrian Navigation System is developed utilizing an algorithm based on the Modified Receding Horizon Kalman Finite Response Filter (MRHKF). The PNS consists on a two-axes accelerometer and a two-axes magnetic compass mounted on shoe and Azimuth orientation and steps are calculated.

Hence, the Kalman filter minimize the variance of the estimated mean square error. But the problem is that it depends on predefined dynamics model. To achieve good filtering results, it is required to know the complete a priori knowledge of the dynamic process and measurements models. In addition, the Kalman filter introduces a delay in the output of the filtered signal.

For these reason, different approach are utilized instead of Kalman filter for fusing the sensors data. (Kappi, 2001) utilizes gyroscopes for the Heading system, and corrects the drift with a digital magnetic compass compensated by accelerometers. A use of a gyro-free personal navigation systems is discussed in (Collin, 2002). The systems integrate the data of a 3D magnetometer, a 3D accelerometer and a barometric altimeter. In (Ladetto, 2002b) an integration of gyroscope and magnetic compass is proposed. The algorithm checks the presence of magnetic disturbance. If both the sensors, comparing the respective orientation indication, do not turn at the same time, a magnetic disturbance is detected. The only valid data for the orientation is considered the gyroscope output.

One of this approaches which utilizes the integration of gyroscope and magnetic sensors information is proposed in Paragraph 6.4.

The theory which concern the estimation of position starting from information derived from Inertial and Heading systems will be discussed in Paragraph 5.2.1

5.1.10 Integrated Technologies

The idea behind integration of different technologies is the same of the data fusion one: characteristics of one type of technology are used to overcome the limitations of the others.

As seen in the Paragraph 5.1.1.1, the GPS in constrained environment needs a hand from other technologies. On the other hand, the Inertial and Heading systems need to fix the initial orientation and position, to correct the error in the positioning during the walking due to the sensors drift, and to calibrate some system parameters. There are several work concerning the integration of GPS Inertial Navigation System or Heading Systems. Some examples are provided.

(Cannon, 2001) try to demonstrate the feasibility of using a low-cost motion sensor system integrated with a DGPS to provide accurate position and attitude information. Also, advanced algorithms are proposed to integrate the sensors and the GPS.

In (Hide, 2003) is investigated the use of the integration of GPS and low-cost inertial sensors utilizing all the thee techniques of Adaptative Kalman filtering. (Hide, 2006) proposes the same algorithm utilizing the more recent HSGPS instead of the classical GPS. In this paper is also proposes a comparison between the explained algorithm and an high accuracy integrated GPS/INS which is used to provide a reference trajectory. With respects to the utilization of an Adaptative Kalman filter, the utilization of a online stochastic modeling of the system and a new adaptative process noise scaling algorithm is proposed in (Ding, 2007). A synergy from two different Adaptative Kalman Filter (the IAE and the AFKF) is proposed in (Jwo, 2008) concerning the integration of different sensors and the integration of Inertial sensors and GPS.

A method for correcting Navigation parameters (heading and step size) is proposed in (Jirawimut, 2003a). This system integrate the GPS system and a pedometer based on magnetic sensor and accelerometers. During the measured time interval between two successive steps, if the GPS signal is available, the compass bias error and the step size error are estimated. This integration is performed using a Kalman filter with inputs the steps period and the heading, the GPS position and the velocity. The output of the Kalman filter (when the GPS signal is available) are the position, velocity, the step size error and the compass bias error.

Also (Wang, 2004) presents the integration of GPS and gyroscopes utilizing a Kalman filter. In this case the application considered is finding the people attitude. It is demonstrated that the integration of the two improves with respect to utilizing the GPS standalone since the attitude parameters can be estimated using the angular rate measurements from rate gyroscopes during GPS outages.

(Zhang, 2008) describes a tightly-coupled un-differenced GPS/INS integration, utilizing un-differenced GPS instead the differenced GPS. In this manner the costs of the system are low and the receiver station is no needed, when it is needed near in the differenced GPS.

Inertial Tracking Systems can be also integrated with Radio Frequency technologies. (Wang, 2007) proposes a pedestrian tracking framework based on particle filter which integrates the typical WLAN indoor positioning with low cost accelerometers and map information.

The integration of Inertial Sensors and Stereo Cameras is investigated in (Jirawimut, 2003b). The method is based on the knowledge of a the Gait cycle enabling to operate with walking users.

The integration of different techniques for find the position of pedestrian users are exposed in the works of Retscher. In (Retscher, 2007) are integrated together: GPS, digital compass and gyroscopes for heading estimation, accelerometers for the determination of the distance traveled, a barometric pressure sensor for altitude determination and position determination using Wi-Fi fingerprints. All the technologies are integrated together using a Kalman filter. Tests and results are shown. The main methods are well compared and described in (Retscher, 2006a).

5.2 User Positioning Principles

Taking into account the above mentioned positioning technologies, various methods to detect the position of a user or object are presented. (Pettinari, 2007) reports and characterize a list of these positioning methods:

- Proximity: it detects when the mobile entity is inside the coverage range of radio, ultrasound or infrared signals. It can be performed via physical contact or wirelessly. It is very popular because it requires few modification of the infrastructure and quick positioning, but it lacks in precision.
- Angulation: it is a geometric technique that involves the measurement of a signal approaching different receivers at known position. Angulation is also know as angle of arrival (AoA).The drawback of this method is the interference caused by reflected signals in multi-path conditions.
- Lateration: it computes the position of an object by measuring its distance from multiple reference positions. Lateration techniques include two general approaches: “*time-of-flight”* measurement (measurement of a signal from a transmitter to a receiver) and “*attenuation*” measurement (measurement of signal strength relative to its original intensity).
- Pattern matching: it uses features of a scene observed from a particular point to compute the position of the object. Observed features are looked up in a predefined dataset that maps them to object positions. Differential scene analysis tracks the difference between successive scenes to estimate position. The advantage of scene analysis is that the position of objects can be inferred using passive observation and features that do not correspond to geometric angles or distances. Disadvantages include the fact that the observer needs to have access to the features of the environment against which it will compare its observed scenes.
- Dead Reckoning Navigation: it is one of the earliest and largely used approach in positioning systems applied first by sailors. It is a relative navigation technique. Starting from a known

position, successive displacements are added up. The displacements estimates can be in the form of changes in Cartesian coordinates or in Heading and speed or distance.

The approach studied and developed in this PhD work is the Dead Reckoning Navigation, which will be highlighted in the following sections.

5.2.1 Dead Reckoning Positioning

Dead Reckoning positioning techniques has been shown to yield positioning accuracy adequate for many applications. The technique estimates the user's current position based on a previously determined position. The starting position has to be known. The displacements computed are generally expressed in terms of changes in Cartesian coordinates, *i.e.* x and y coordinates (**Errore. L'origine riferimento non è stata trovata.**). The coordinates of the i*th* displacement can be computed as in Fig. 5. 2 knowing the displacements for this passage (d_i) and the Heading ($Heading_i$). For Heading is meant the direction of movement of the physical object in the reference system considered.

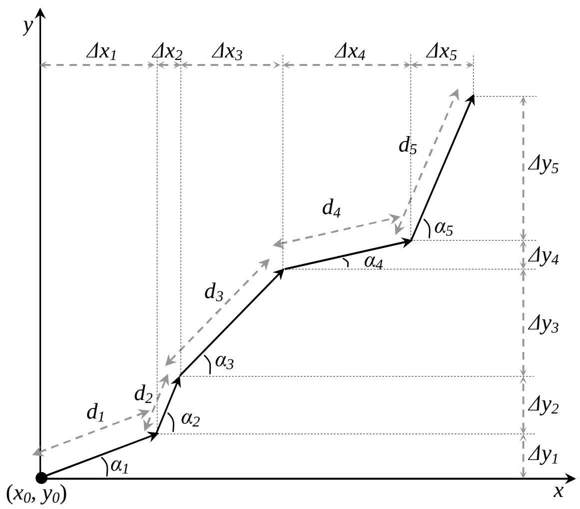


Fig. 5. 1 Dead Reckoning Positioning Principle

The Dead Reckoning is usually based on Inertial Sensors and Heading sensors (see Paragraph 5.1.9): accelerometers, gyroscopes and sometimes their integration with magnetic sensors which provide the orientation of the user (or object) in respects to the Geographical North. The utilization of this sensors are relatively inexpensive and can easily be engineered into existing personnel clothing and procedures.

Dead Reckoning positioning includes two different approaches:

- Inertial Navigation
- Step and Stride Detection

The latter processes the motion's equation of the centre of mass of the moving body, estimating the position by means of a double integration of the accelerations. This approach suffer of two problem: there is the necessity to align the orientation of the axes of the Inertial Navigation System with respect to the reference axis system, and the inherent systematic errors present in the system quickly accumulate to non permissible positioning errors. Such characteristics do not allow to compute the position by double integration of the accelerations. The first problem is solved by means of rotations matrix. The accumulation of the error in the double integration is due to the accelerometer drift caused by the Thermo-Mechanical White Noise. This error is also called Velocity Random Walk because causes a spurious velocity by integrating the acceleration (Thong, 2004; Woodman, 2007). This thermal noise and the other error source of the accelerometer will be exposed in Paragraph 6.1.

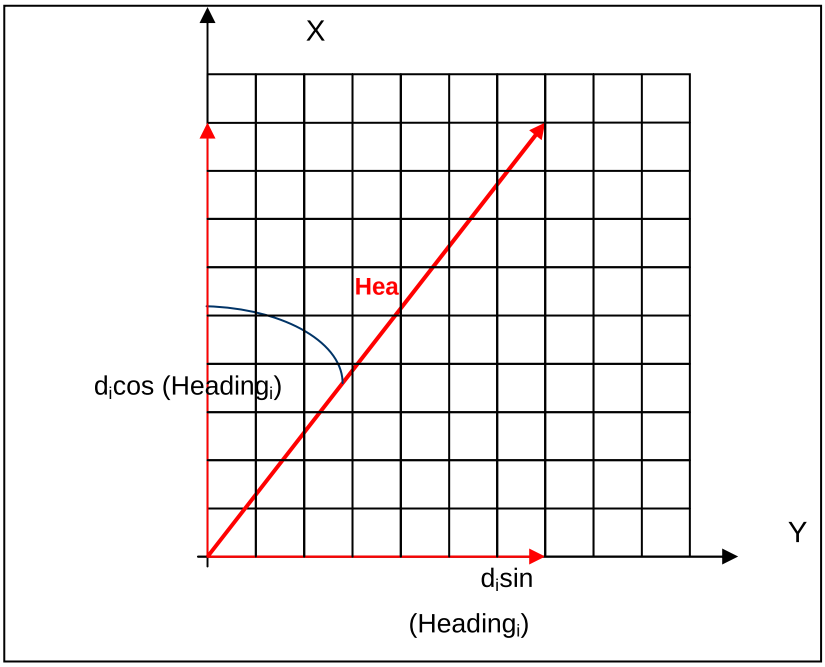


Fig. 5. 2 Dead Reckoning Coordinate Calculation

Several work use the double integration to compute the position To solve the problem of the Velocity Random Walk it is utilized drift correction procedures. (Xiaoping, 2007) utilize a drift correction method based on the fact that the nature of the walking is periodic and includes periods of zero velocity when the foot is in contact with the ground. Other approaches manipulate the accelerations without computing drift correction. (Beauregard, 2007) utilizes a shoe-mounted sensors and inertial mechanization equations to directly calculate the displacement of the feet between footfall. Initially, it is used a rotation matrix that bring the sensor coordinates to the real world coordinates. Then the resulting accelerations are double integrated to yield the displacements. The same approach is proposed in (Torres, 2007) where the gravity, centripetal and tangential components of the acceleration are removed from the motion acceleration to obtain the linear acceleration utilizing rotation matrix. In this manner also the orientation of the user is computed in the Earth's reference fixed frame. In (Leppakoski, 2002) an acceleration magnitude signal from the three accelerometer axes is first calculated. Then step boundaries are defined by the positive going to zero crossing of a low-pass filtered version of this signal. The acceleration magnitude's maximum, minimum and variance values of each steps are determined. The integral of the acceleration magnitude between footfall is also calculated. In (Cho, 2002) a double integration of accelerations is performed applying method to compensate the accelerometer errors utilizing the walking characteristics.

To avoid the necessity of rotation of reference systems, an external initial alignment can be computed as seen in the Paragraph 5.1.9. This initial alignment permits to assign to the coordinates of the starting points, the initial orientation and the initial velocity. This can be performed utilizing infrastructure dependent technologies (such as RFID, hot spot Wi-Fi…) or magnetic sensors which report the coordinates in the Earth's coordinates.

To avoid the *a priori* knowledge of the accelerations, the Step and Stride Detection methods is widely utilized. These are based on the estimation of the pedestrian steps and of their length observing the walking accelerometers patterns. This is equivalent to divide the path in sub-paths which are equivalent to the users' steps. The displacements are then the steps and if the length of each steps is computed, the coordinates of the displacements can be computed as in Fig. 5. 2. It is therefore important to determine the step occurrences and the step length. The theory of step detection and two approaches are proposed in Chapter 8.

5.2.2 Step Length Estimation

The stride in a Dead Reckoning system is a time-varying parameter. The predetermined stride cannot be used effectively for the distance measurement because the strides of a walker are different according to the human parameters. The stride depends on several factor such as walking velocity, step frequency, height of a walker… As the stride is not constant and can change with speed, the step length parameter must be determined continuously during the walk to increase the precision. Several methods are proposed to estimate the stride length. (Zijlstra, 1997) use a triaxial accelerometer to measure step length and an algorithm based on an inverted pendulum model to predict the body centre of mass trajectory during walking. The method determines foot contacts by monitoring for changes in sign of the forward acceleration of the lower trunk. (Sagawa, 2000) uses a triaxial accelerometer and a single axis gyroscope attached to the toe to measure gait parameters and distance travelled. The same approach is utilized in (Cavallo, 2005; Scapellato, 2005) by means of a biaxial accelerometer and a single axis gyroscope. An improved method of measuring foot angle using parallel offset accelerometers to measure angular acceleration of foot which is integrated twice to yield foot angle avoiding the inherent bias drift in gyroscopes, is proposed in (Fyfe, 1999). Accurate over a wide population without requesting user calibration, this technique is valid for a complete range of gait velocities. The works of Sagawa and Fyfe rely on the assumption that the foot motion is primarily in the sagittal plane. However these methods have a possible advantage over empirical models in that they measure steps length directly.

(Jirawimut, 2003a) modelled the step length error as a first order Gauss-Markov model and the step length is estimated using a Kalman filter and a GPS.

The step length is modelled as a linear combination of a constant and step frequency in (Levi, 1996), in (Ladetto, 2000; Shin, 2007) as a linear combination of a constant, step frequency and variation of accelerometer, in (Kappi, 2001) as a linear combination of step frequency, variance of the measured acceleration magnitude and vertical velocity, in (Gabaglio, 2001) as a linear combination of a constant and a function of acceleration variability, in (Lee, 2001) as a linear combination of the ratio of step size and the step rate and in (Shin, 2007) as a linear combination of walking frequency and a variance of the accelerometer signals during a step.

(Stirling, 2003) shows how, once the stance phase is identified, the initial foot angle can be determined. The foot angle profile is calculated by double integration of the angular acceleration profile. Once the foot angle is known, it is used to resolve the horizontal component of acceleration from the sagittal plane acceleration signals, which is integrated to horizontal velocity. The average horizontal velocity is multiplied by the stride duration to yield the stride length.

(Aminian, 1993) proposes a neural network to estimate the inclination and the walking speed. Also (Cho, 2006) using a neural network in which the inputs are the walking information.

Some experimental method to detect the step length are proposed. For example in (Kim, 2004) is presented an experimental relationship between measured acceleration and stride which is used for online estimation of the stride. Another empirical relationship is utilized in (Antsaklis, 2005; Weinberg, 2009a) where the step length is approximated utilizing the formula:

$$StepLength = K\sqrt[4]{A_{ZMAX} - A_{ZMIN}} \qquad \textbf{Eq. 5. 1}$$

where A_{ZMAX} and A_{ZMIN} are the maximum minimum value of the vertical acceleration and *K* is a user dependent constant. This formula is utilized for sensors applied on waist.

In this PhD work the last methods is utilized. Since most of the step length estimation algorithms depend on user or user parameter, procedures to calibrate the methods are required. In the following section some step calibration methods are exposed.

Step length estimation errors often occur during starts, stops, sharp turns and walking on inclines. Some researchers have attempted to overcome these limitation by using phase relationship between the up/down, left/right, forward/backward accelerations, but it is not clear how a large variety of locomotion patterns could be modelled properly in this way. A study of the pattern of some movements is proposed in the Chapter 8.

5.2.3 Step Calibration Methods

The step size is dependent on several factors. The main one are the velocity and the step frequency of the user. Online or offline calibration methods which takes into consideration the characteristics of the user have to be implemented for the most step length algorithms. These methods often are helped by other technologies. For example in (Gabaglio, 1999) a real-time step calibration algorithm is proposed using a Kalman filter with GPS positioning measurement and three estimated parameters: frequency, amplitude and mean. These parameters are obtained from another Kalman filter whose input is the measured z-axis acceleration. Also in (Jirawimut, 2003a) the step size is calibrated utilizing a Kalman filter when the GPS signal is available. In (Dippold, 2006) a step length calibration based on particle filter is implemented. The filter utilizes only the user position with respect to the building infrastructure. In (Ladetto, 2000) an adaptative Kalman filter is used to recalibrate the individual parameters of the Fast Fourier Transformation utilized to calculate the step length.

An initialization procedure with physiological inputs such as body height, leg length and weight is proposed as start of displacements determination in (Ladetto, 2002b). (Pettinari, 2007) proposes two methods to calibrate the K constant of the Eq. 5.1: through the Stereo Camera and through a GPS receiver. In the latter approach the Dead Reckoning system provide user tracking information filling the gaps between the areas covered by the Vision Tracking System installed in the ceiling. Then the Vision Tracking System provides the initial position and orientation. To calibrate the K constant, when the user is in the field-of-view of the camera, for every step detected by the Dead Reckoning system, the algorithm estimates the Vision Tracking System step length, by considering the Vision Tracking System position in the same instant in which the Dead Reckoning system detects a new step. In this way, when two successive steps are detected the system estimates the VTS step length and it is possible utilizing a mathematical proportion estimate of the K constant. The former approach utilizes a GPS receiver. When the GPS signal is available and if the walk is straight, the mean value of the step length estimated by the GPS is compared with the mean value of the step length detected by the Dead Reckoning system.

An approach performed not during the normal functioning and without the utilization of supported infrastructure is proposed in this work for calibrate the K constant (Eq. 5.1) of the user who wear the Dead Reckoning system. If the user walk a straight line of predefined length ($TotalTrueDistance$) and he or she is wearing a Dead Reckoning system in which the K constant is imposed to 1, the step length can be calculated by mean of Eq. 5.1 and the mean of the step length can be detected ($AverageStepLength$). If it is present an algorithm to detect the step occurrences, the total number of steps is detected ($TotalTrueSteps$). The K constant can be calculated by means of a simple mathematical proportion:

Eq. 5. 2

$$K = \frac{TotalTrueDistance}{AverageStepLength * TotalTrueSteps}$$

5.3 Multi-Sensor Approach for Pedestrian Positioning

As seen the Dead Reckoning systems integrates Inertial and Heading technologies utilizing inertial sensors (such as Gyroscopes and Accelerometers). The integration of inertial sensors with magnetic sensor is considered as a Dead Reckoning system in which the initial position and orientation can be set by means of the magnetic sensor. Therefore, the Dead Reckoning system can be seen as a Multi-Sensor system. This definition is utilized in this work.

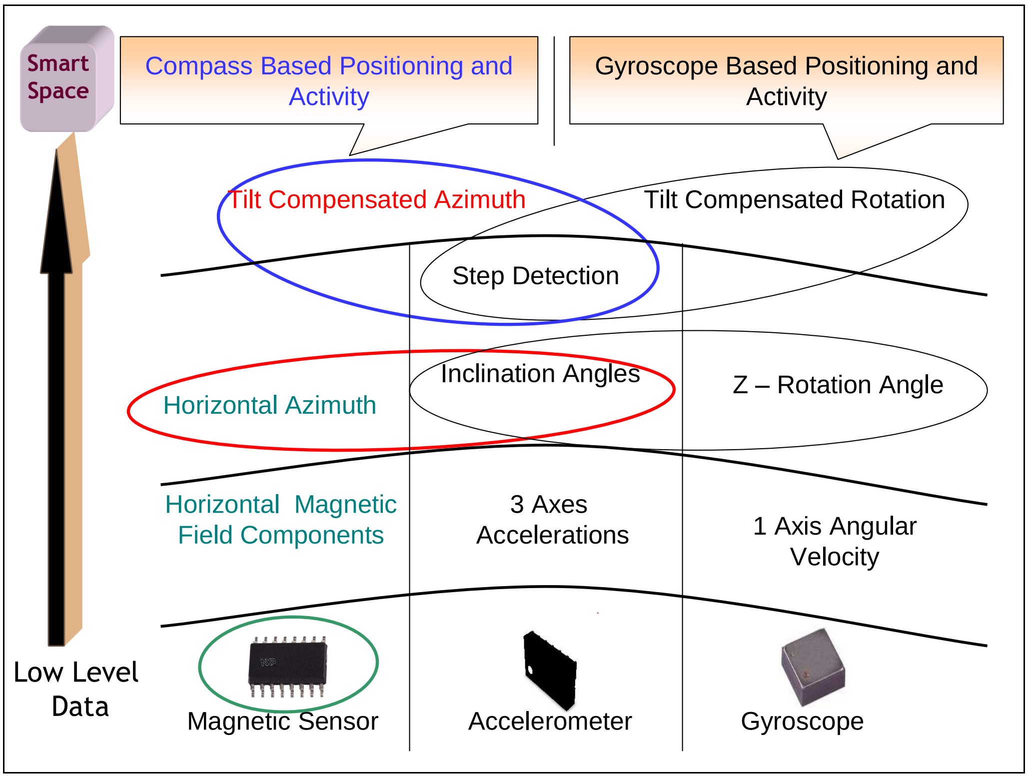


Fig. 5. 3 Multi-sensor approach: from low level sensors to the Semantic Space

In the Multi-Sensor systems the integration of more sensors can be utilized to extract from the low level data, *i.e.* the data extracted from the sensors, high level data which can be inserted in the Smart Space. In the Fig. 5. 3 this idea is exposed: in the lower line the sensors are present. In this case the sensors are: a *two-axes magnetic sensors*, a *three-axes accelerometers* and *one-axes gyroscopes*. From this sensor the first level data are extracted (second line) which are: the *horizontal magnetic field components* from the *magnetic sensor*, the *three axes accelerations* from the *accelerometer* and the *angular velocity* from the *gyroscope*. The third line shows that from the *horizontal magnetic field components* the *horizontal Azimuth* (horizontal rotation angle with respects to the Geographical North) can be extracted, from the *accelerations* the *inclination angles* can be extracted, from the *angular velocity* the *Z rotation angle* can be extracted. The forth line shows that from the accelerations the *steps occurrences* can be detected. The fifth line shows the sensors combinations: utilizing the *inclination* *angles* and the *horizontal Azimuth*, the *Tilt-Compensated Azimuth* is computed; utilizing the *inclination angles* and the *Z rotation angle*, the *Tilt-Compensated Rotation* is computed. The Dead Reckoning high level data are shows in the highest line: combining the *steps occurrences* and the Tilt-Compensated orientation or derived from the magnetic sensor or derived from the gyroscope, *positioning* and *activity* information are extracted.

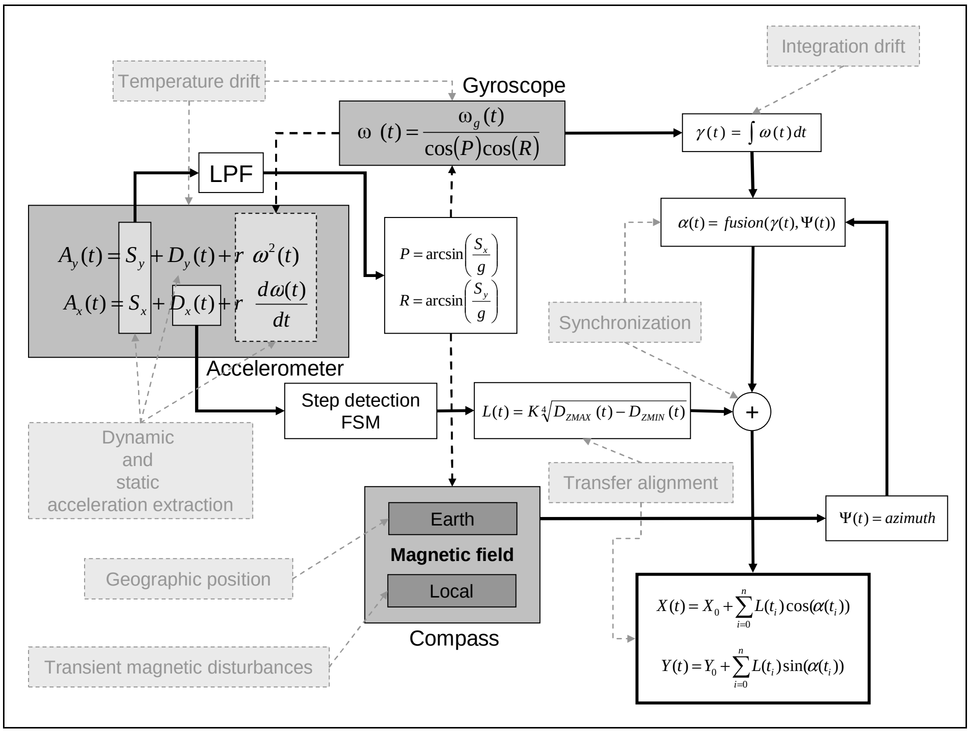


Fig. 5. 4 Sensors Correlations

As it will be seen better in Chapter 6 and 7, besides the exposed correlations, sensors have hidden correlations. In Fig. 5. 4 all these are shown:

- the accelerations are composed of static and dynamic components. To compute inclination angles, only static accelerations has to be utilized. To detect steps only dynamic has to be utilized;
- gyroscope and accelerometer are affected by the temperature drift;
- compass is affected by spurious magnetic disturbances;
- compass is necessary to impose to the Dead Reckoning system the initial position and to refer the system to the Earth's reference system;
- gyroscope angular velocity is utilized to compute the rotation angle along the Z axis. This computation is affected by the integration drift;
- the orientations derived from the compass and from the gyroscope could be fused. In this case the synchronization important.

5.3.1 Multi-Sensor Platforms for Pedestrian Navigation

The Multi-Sensor approach in the Dead Reckoning systems is particularly utilized. Several platforms are developed both for commercial and research purposes. Table 5. 4 synthesizes some famous Pedestrian Navigation systems based on Multi-sensor approach and their most important characteristics.

Name	Sensors	Dimensions	Characteristics
PINPOINT (Univ.Lancaster) (Bandala, 2007)	3-D magnetic sensor 3-D gyroscope	50 x 50 x 50 mm	6 DOF Resolution: 2 mm in position 0.2° in orientation
Intel MSU (Lester, 2005)	3-D accelerometer 3-D magnetometer Temperature audio IR-light Barometric pressure Humidity	6.43 x 6.43 x 6.43 cm	Utilized for Activity Recognition
NavMote (Antsaklis, 2005)	3-D accelerometer 3-D magnetometer GPS	31 x 33 x 13.5 mm	Azimuth Accuracy: 0.5° Utilized for pedestrian tracking: distance accuracy: ±3% heading accuracy: 1 °
MARG Sensors (Bachmann, 2003)	3-D accelerometer 3-D magnetometer 3-D gyroscope	10.1 x 5.5 x 2.5 cm	Orientation Accuracy: 0.001° at [0.001, 80] °/s
WIHU Module (Torres, 2007)	3-D accelerometer 3-D magnetometer 3-D gyroscope	25 x 25 x 25 mm	6 DOF Gyroscope sensitivity: 2% Accelerometer sensitivity: 5%
NAVIO system (Retscher, 2006a)	GPS 3-D accelerometer 3-D magnetometer barometric altimeter		Altitude deviation: ±1m Position deviation: ±1-3 m

Name	Sensors	Dimensions	Characteristics
POSLV	GPS 3-D accelerometer 3-D magnetometer	908 x 115 x 254 mm	Position error in land: 1.29 m
DRM ™ 4000 (Honeywell, 2002)	GPS 3-D gyroscope 3-D accelerometer 3-D magnetometer barometric altimeter	51 x 51 x 12.7 mm	Accuracy 2% on distance Azimuth Accuracy > 1°
InertiaCube (Intersense, 2009)	3-D Accelerometer 3-D gyroscope 3-D compass	2.62 x 3.92 x 1.48 mm	3 DOF Rotation accuracy: 0.25° Sensibility: 0.03°
MTx (XSENSE, 2009)	3-D Accelerometer 3-D gyroscope 3-D compass	3.8 x 5.3 x 3.1 cm	Sensibility: 0.05° Rotation accuracy: 0.5°
DMC-SX-5000 (Vectronix, 2008)	3-D accelerometer 3-D magnetometer	33 x 31 x 13.5 mm	Rotation accuracy: 0.25° Elevation Accuracy: 0.1°
AEK-4 (u-blox, 2008)	Odometer Digital speed Linear accelerometers Radar, optical, acoustic sensors Gyroscopes Magnetic compass GPS	74 x 54 x 24mm	Sensitivity Acquisition:-140 dBm Sensitivity Tracking:-150 dBm Operational limits Velocity:500m/s
Circinus (Atairaerospace, 2010)	3-D Gyroscopes 3-D Accelerometer 3-D Magnetometer GPS	7.62 x 3.81 x 1.43 mm	Position accuracy: 2 m Velocity Accuracy< 0.2 m/s Rotation Accuracy < 2.0° Resolution < 0.25°
3DM-GX2 (Microstrain, 2009)	3-D Accelerometer 3-D gyroscope 3-D magnetometer	4.1 x 6.3 x 3.2 cm	Orientation Resolution: <0.1° Orientation Accuracy: ±

			0.5°
Name	**Sensors**	**Dimensions**	**Characteristics**
Crista IMU (CloudCap, 2010)	3-D Accelerometer 3-D gyroscope	5.21 x 3.94 x 2.5 cm	Gyroscope range: ±300°/s scale factor error<3°/s Accelerometer:range: ±10 g scale factor error<10mg
FalconGX (O-Navi, 2010)	3-D Accelerometer 3-D gyroscope	5.97 x 3.18 x 1.52 cm	Angular Rate Resolution: 0.30°/sec Acceleration Resolution: 4mg
nIMU (Memsense, 2010)	3-D Gyroscope 3-D Accelerometer 3-D Magnetometer	4.65 x 0.546 1.39 x 2.29 cm	Acceleration non linearity: ±0.4% Angular rate non linearity: ±0.1%
3D Motion Sensor (Nec-Tokin, 2010)	3-D Gyroscope 3-D Accelerometer 3-D Magnetometer	20 x 20 x 15 mm	6 DOF Orientation Resolution: 1° Maximum orientation error: ±10°
Terrella 6 (MassMicroelectronics, 2010)	3-D Gyroscope 3-D Accelerometer 3-D Magnetometer Temperature Pressure	97.8 x 16.5 x 13.2 mm	Compass Resolution<0.2° Compass Accuracy<11° Inclination Resolution<0.2° Inclination Accuracy<1°
MAG02 (OmniInstruments, 2010)	3-D Gyroscope 3-D Accelerometer 3-D Magnetometer	1.8 x 1.8 x 1 mm	Accelerometer Sensitivity: 1 V/g Gyroscope Sensitivity: 12.5mV/°/s

Table 5. 4

5.4 Pedestrian Positioning System Requirements

The goal of a Pedestrian Positioning system is to provide user position anywhere and anytime. To perform this task, several technologies and methods have been proposed. Each one of these technologies and methods posses its performance and its characteristics. In Table 5. 1 Retscher provides some prerequisite that the different technologies has to provide to be a Pedestrian Navigation system.

These requirements can not be taken as strict because every system depend on the operational conditions, from the cost and from the application in which every one has to operate.

For all the above mentioned reasons, application personalized requirements have to be analyzed and implemented for every Pedestrian Navigation System.

The application which concerns this PhD work has as targets the navigation in public buildings, the guides for museums and archaeological sites and in general all the multi-vendor, multi-device and multi-domain applications where user positioning and tracking in spaces is required (*e.g.* health and monitoring applications). In this work will be reported the study, development and realization of Pedestrian Navigation System for shared and interoperable Smart Spaces.

Therefore, the application has to be supported by a Smart Environment. Taking into consideration the target of the applications, the study of the requirements have been the first step of this work. The considered requirements can be divided in: Quality, Functionality and Performance. For a Pedestrian Navigation System, the Quality requirements can be:

- Wearability: the system has to be portable and easy to wear
- Low Power Consumption: since the system has to be portable, the power supply is a battery. Power consumption specification are thus necessary
- Testability: the developed system is a research system. The testability is the ability to test the system everywhere
- Ease of Calibration: the developed system has to be calibrated. Several research in this field are conducted to make easy the calibration procedures.

The functional requirements are the functionalities that the system can provide. These can be expressed as:

- Orientation: as seen, the system has to provide the orientation to compute the position
- Relative Position: as seen, the relative position can be extracted from the step length detection and orientation. The integration with other systems permits to initialize the position and to translate the relative reference system into a known frame
- Activity Indication: this kind of system can express also various level of activity recognition. For example if the user walking or not.
- Wireless Communication: the system has to be portable. Wireless communication towards the Smart Space has to be supported
- Semantic Platform Integration: to extract high level data, which are not extractable from the Inertial Platform, the integration into the Smart Space is necessary.

Regarding the Performance Requirements, these are the results of the integration of sensors and algorithms. The reachable Performance Requirement in the target applications can be:

- Azimuth Max Deviation = ±3° when Tilt less than ±30°

- Tracking Error minor of 3% on a 100 m walk in a flat area

Chapter 6

Static Direction Estimation Using a One Axis Gyroscope and a Two Axes Accelerometer

In this chapter it is presented the project of the entire hardware and software platform which permit the estimation of static direction through a one axis gyroscope and a two axes accelerometer. The presence of a magnetic compass integrated in the system is investigated.

In particular, in Paragraph 6.1 accelerometers and gyroscopes theory is introduced, in Paragraph 6.2 is highlighted the hardware and software acquisition chain, the calibration algorithms (and the consequent calibration procedures) are expanded in Paragraph 6.3 and the data fusion algorithms from which derive the orientation information is explained in Paragraph 6.4.

6.1 Gyroscopes And Accelerometers Theory

In this Paragraph is presented an overview of the two sensors utilized to estimate the static direction: Accelerometer and Gyroscope.

There are various typology of accelerometers, but the basic operating principle is essentially the same: the detection of the inertia of a spring mass (also known as seismic mass) when subjected to acceleration. In the presence of an acceleration, the mass moves from its static position proportionally to the acceleration detected. The sensor circuitry converts the mass movement (mechanical quantity) into an electrical signal (Löttersa, 1998), (Ferraris, 1995), (Johnson, 2006).

When static, the accelerometers are sensitive only to the gravitational acceleration. During the movement, they are sensitive to the gravitational acceleration and to the dynamic accelerations induced by the movements (centripetal and tangential). Therefore the output represents the vector sum of dynamic and gravitational accelerations.

The most common types of accelerometers are based on *piezo-resistivity*, *piezo-electricity* and on *capacitive* technology (Johnson, 2006):

- *piezo-resistive* accelerometers (Silicon, 1983): the *piezo-resistive* elements are directly connected to the mobile mass and they change their resistor value when subjected to the length variation due to the mass movement. The resistor variation is easy to detect, and for this reason the *piezo-resistivive* technique is widely utilized. The major disadvantages of using this accelerometers, are that output signal level is normally low (a typical value is 100 mV for 10V power voltage), the temperature coefficient is high and there is the presence of thermal noise due to the resistor.
- *piezo-electricity* accelerometers: the sensing element is made of a *piezo- electric* material that, generates an electric signal proportional to the vibratory forces. Normally, for the accelerometers are used natural oscillating materials, such as the quartz, or artificial oscillating material. In the *piezo- electric* accelerometers the mass is suspended on the *piezo- electric* part. In the presence of acceleration, the mass comprises the *piezo- electric* part which generates a signal proportional to the compression. The major characteristics of this type of accelerometers are:
    - they have a relatively low sensitivity;
    - they can detect very high accelerations without damaging (also 1000 g);
    - they can not detect continuous acceleration and static, because after a few seconds from the application of the acceleration, the signal fades in.
    - they have a good sensitivity;
    - they have little dimensions.
- *capacity* accelerometers (Analog, 1965), (Freescale, 2010), (VTI, 1991): they are built in silicon and are based on the intrinsic property of capacitor: the capacity is directly proportional to the distance between the plates forming the capacitor. In the sensor are present two differential

capacity formed by the moving mass. Any moving of the mass corresponds to a variation of the individual capacity. The difference in capacity can be converted to a voltage output signal, through synchronous demodulation techniques.

Appendix C presents a comparative analysis of some accelerometers.

The accelerometers are affected to various error (Kinney, 1999; Woodman, 2007), modelled through the following components:

- Constant Bias: the bias of an accelerometer is the offset of its output signal from the true value, in m/s^2. A constant bias error ε, when double integrated, causes an error in position which grows quadratically with time. The accumulated error in position is:

  $$s(t) = \varepsilon \frac{t^2}{2}$$ s(t)

  where *t* is the time of integration.

  It is possible to estimate the bias by measuring the long term average of the accelerometer's output when it is not undergoing any acceleration. Unfortunately this is complicated by gravity, since a component of gravity acting on the accelerometer will appear as a bias. It is therefore necessary to know the precise orientation of the device with respect to the gravitational field in order to measure the bias. In practice this can be achieved by calibration routines in which the device is mounted on a turntable, whose orientation can be controlled extremely accurately.
- Thermo-Mechanical White Noise / Velocity Random Walk: the output samples obtained from a MEMS accelerometer are perturbed by a white noise sequence. Integrating white noise produces a random walk whose standard deviation grows proportionally to $\sqrt{t}$. Hence white noise on the output of an accelerometer creates a velocity random walk. To see what effect accelerometer white noise has on the calculated position it can be done a similar analysis in which it is double integrated samples obtained from an accelerometer. This analysis shows that accelerometer white noise creates a second order random walk in position, with zero mean and a standard deviation which grows proportionally to $t^{3/2}$.
- Flicker Noise / Bias Stability: MEMS accelerometers are subject to flicker noise, which causes the bias to wander over time. Such fluctuations are usually modelled as a bias random walk. Using this model, flicker noise creates a second order random walk in velocity whose uncertainty grows proportionally to $t^{3/2}$, and a third order random walk in position which grows proportionally to $t^{5/2}$.
- Temperature Effects: as with gyroscopes, temperature changes cause fluctuations in the bias of the output signal. The relationship between bias and temperature depends on the specific device, however it is often highly non-linear. Any residual bias introduced causes an error in position

which grows quadratically with time. If the IMU contains a temperature sensor then it is possible to apply corrections to the output signals in order to compensate for temperature dependent effects.

- Calibration Errors: calibration errors (errors in scale factors, alignments and output linearity) appear as bias errors which are only visible while the device is undergoing acceleration. Note that these 'temporary' bias errors may be observed even when the device is stationary due to gravitational acceleration.

For a more broaden explanation of Accelerometers error, please see (Thong, 2004).

Accelerometers is used to calculate the inclination angles (called *tilt*) (Leavitt, 2004). In fact, in static condition, a rotation can be decomposed into two rotations with the horizontal plane:

- One rotation around the axis X (inclination of the axis Y), represented to the angle called *Roll* (Φ)
- One rotation around the axis Y (inclination of the axis X), represented to the angle called *Pitch* (Θ)

The Pitch and Roll angles are called *Tilt* angles and they can be obtained, in static conditions, to the static accelerations in a plane parallel to the Earth's surface, with the following formulas:

$$Pitch = \arcsin \frac{A_x}{g}$$ **Eq. 6. 1**

$$Roll = \arcsin \frac{A_y}{g}$$

where g is the gravitational acceleration, A_x and A_y are the static components of one accelerometer in the horizontal plane. The tilt angles calculations, do not suffer from integration drift.

The gyroscope is a sensor which permits to detect the angular velocity and the rotation angles of a moving body. The physical basic principles are the conservation of the angular momentum and the Newton's law. The basic mechanism is a wheel rotating around its board. When the wheel is spinning, its axis tends to remain parallel to itself and to oppose any attempt to change its orientation. A gyroscope shows a series of phenomena, including the Precession and the Nutation. The Precession is a change in the orientation of the rotation axis of a rotating body, the Nutation is a slight irregular motion in the axis of rotation of a largely axially symmetric object.

The fundamental equation of the gyroscope is:

$$\tau = \frac{dL}{dt} = \frac{d(I\omega)}{dt} = I\alpha$$ **Eq. 6. 2**

where:

τ is the torque,

L is the angular momentum,

I is the inertia vector,

ω is the angular velocity,

α is the angular acceleration.

From the equations derives that if is applied a torque τ perpendicular to the rotation axis (perpendicular to *L*), it develops a force perpendicular to both τ and *L*. The derived motion is the precession. The angular velocity of the precession motion (Ω_P) is:

$$\tau = \Omega_P \times L \qquad \textbf{Eq. 6. 3}$$

The most common types of gyroscopes are RLG, FOG and MEMS (Söderkvist, 1994):

- *Ring Laser Gyroscope* (RLG) (RingLaser, 1985): this type of gyroscopes is very expensive but very accurate in the detection of the angular velocity. It is constituted to a laser beam enclosed in a closed triangular two-way path, with mirrors at each corner and an interferometer. The beam makes a tour of the path with constant frequency when the gyroscope is in a static condition. If the gyroscope is rotating, the frequency with which the beam makes a tour varies in depending on the angular velocity
- *Fiber-Optic Gyroscopes* (FOG) (Pavlath, 1994): The FOG is a good accuracy gyroscope, but less expensive than the RLG. The FOG gyroscopes is also constituted of an internal laser beam and a interferometer, but the path is a fiber optical coil. The frequency of the laser beam depends on the gyroscopes variations, *i.e.* the angular velocity.
- MEMS gyroscopes: the MEMS gyroscopes are constituted of a mobile mass suspended by means of an elastic systems which allows the mass to move. This mass are moving inside the gyroscope and their position changing causes a voltage change which depends on the angular velocity of the system which it moves with. The position of the rotating masses can be detected by means of *piezo-resistive* elements or *capacitive* elements.

Appendix C presents a comparative analysis of some gyroscopes.

The gyroscopes are affected by various errors (King, 1998; Woodman, 2007), modelled through the following components:

- Constant Bias: the bias of a gyroscope is the average output from the gyroscope when it is not undergoing any rotation (*i.e*. the offset of the output from the true value), in °/h. A constant bias error of ε, when integrated, causes an angular error which grows linearly with time (εt). The constant bias error of a gyroscope can be estimated by taking a long term average of the gyroscope's output while it is not undergoing any rotation. Once the bias is known it is trivial to compensate for it by simply subtracting the bias from the output.
- Thermo-Mechanical White Noise / Angle Random Walk: the output of a MEMS gyroscope will be perturbed by some thermo-mechanical noise which fluctuates at a rate much greater than the sampling rate of the sensor. As a result the samples obtained from the sensor are perturbed by a

white noise sequence, which is simply a sequence of zero-mean uncorrelated random variables. In this case each random variable is identically distributed and has a finite variance. To see what effect this noise has on the integrated signal it can be done a simple analysis in which it is assumed that the rectangular rule is used to perform the integration. The results are that the noise introduces a zero-mean random walk error into the integrated signal, whose standard deviation grows proportionally to the square root of time.

- Flicker Noise / Bias Stability: the bias of a MEMS gyroscope wanders over time due to flicker noise in the electronics and in other components susceptible to random flickering. Flicker noise is noise with a 1/f spectrum, the effects of which are usually observed at low frequencies in electronic components. At high frequencies flicker noise tends to be overshadowed by white noise. Bias fluctuations which arise due to flicker noise are usually modelled as a random walk. A bias stability measurement describes how the bias of a device may change over a specified period of time, typically around 100 seconds, in fixed conditions (usually including constant temperature). Under the random walk model bias has the standard deviation which grows proportionally to the square root of time.
- Temperature Effects: temperature fluctuations due to changes in the environment and sensor self heating induce movement in the bias. Note that such movements are not included in bias stability measurements which are taken under fixed conditions. Any residual bias introduced due to a change in temperature will cause an error in orientation which grows linearly with time. The relationship between bias and temperature is often highly nonlinear for MEMs sensors. Most inertial measurement units contain internal temperature sensors which make it possible to correct for temperature induced bias effects.
- Calibration Errors: the term calibration errors refers collectively to errors in the scale factors, alignments, and linearity of the gyroscopes. Such errors tend to produce bias errors that are only observed whilst the device is turning. Such errors lead to the accumulation of additional drift in the integrated signal, the magnitude of which is proportional to the rate and duration of the motions. It is usually possible to measure and correct calibration errors.

As seen, gyroscopes are able to detect angular velocity around the axes of the sensor, with high precision. From this data can be derived the rotation angles around the gyroscopes axes integrating on the time interval the angular velocity:

$$RotationAngle = \int_0^t \omega(\tau)d\tau \qquad \textbf{Eq. 6. 4}$$

If the X and Y axes lie in the plane parallel to the Earth’s surface, and the Z axis is upward (coincident to a gyroscope axis) (Fig. 6. 1) in this way can be calculated the *Yaw* angle. Due to the presence of integration, calculating the angles of rotation can be done only for a short period of time. Moreover, a relatively small error due to the temperature effects will introduce large integration errors.

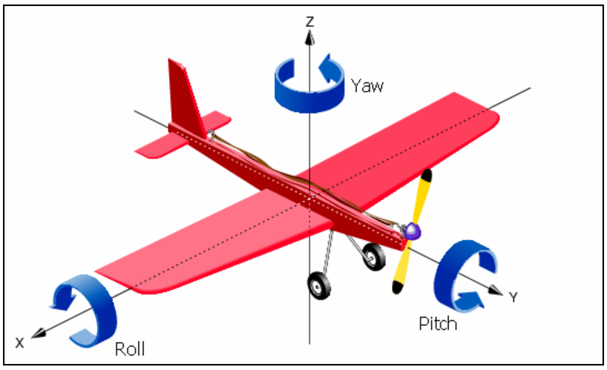


Fig. 6. 1 Rotation Angles

Considering the Z axis of the gyroscope, the detected angular velocity is correlated to the Pitch and Roll angles, because they are the measure of the gyroscope inclination respect to the Z axis. As seen in **Errore. L'origine riferimento non è stata trovata.** when the gyroscope plane is tilted with respect to the horizontal plane, the detected angular velocity ω_d is influenced to the horizontal components. The result is that the detected angular velocity is different to the real angular velocity ω around the Z axis. To take into consideration this tilt influence is necessary a compensation procedure of the angular velocity detected (gyroscope *tilt* compensation) which calculates the vertical angular velocity utilizing the Pitch and Roll angles:

$$\omega = \frac{\omega_d}{\cos\Phi \cos\Theta} \quad \textbf{Eq. 6. 5}$$

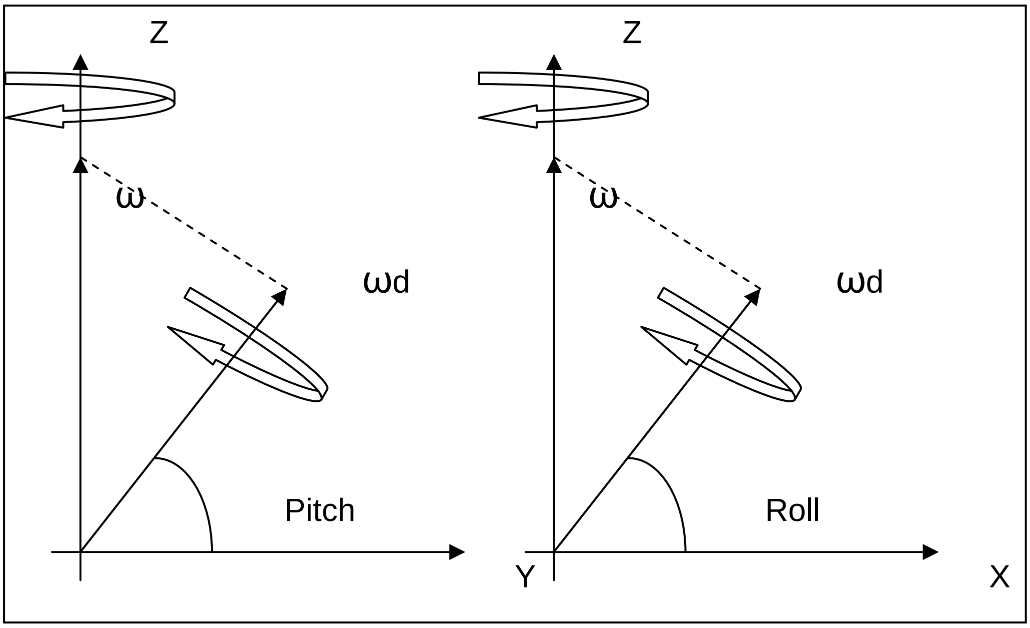


Fig. 6. 2 Gyroscope Pitch and Roll dependency

In the following sections we presents an inertial navigation system for estimating the static orientation based on one-axis gyroscope and a two-axes accelerometer.

6.2 Hardware System Architecture

In this Paragraph are presented the architectural issues and their solutions for the creation of a system to estimate the static direction of a user. This approach is the first one of the two proposed in this work, and it is based on a one-axis gyroscope and a two-axes accelerometer. A two-axes compass is also introduced in the sensor as support to the relative reference system utilized to the gyroscope.

The entire system consists of two parts: the Multi-Sensor-Unit and the power management board. The latter has been already explained in the Chapter 4. In this Paragraph will be presented the project of the entire hardware platform which permits to create the sensor board.

Fig. 6. 3 displays the sensors acquisition block diagram, which can be seen as three macro-blocks:

- the *sensors* block
- the *analog data handling* block
- the *digital data handling* block.

The block diagram represent the steps necessary to transform the low level data into high level data, as shown in Table 6. 1.

Sensor	**Raw Sensor Data**	**High Level Sensor Data**
Gyroscope	- Voltage Analog Output (*AngularVelocity*)	Z- axis rotation angle (*Yaw*)
Compass	- Pseudo- PWM pulse	Angle from the North(*Heading)*
Accelerometer	- X axis PWM pulse - Y axis PWM pulse	X- axis rotation angle (Rolland) Y- axis rotation angle (*Pitch*)

Table 6. 1

In the following sections, the sensor acquisition blocks will be presented.

The first block consists of three *Sensors* which provide the analog raw data:

- a one-axis gyroscope a one-axis Gyroscope ADXRS150ABG (Analog, 2004): this provide an analog output proportional to the angular velocity and a analog output proportional to the temperature. Fig. 6. 4 Voltage Output as a function of angular velocity shows the theoretical gyroscope voltage (V) output as a function of the real gyroscope angular velocity. The gyroscope linear range varies from 0,25V to 4,75V, correspondent to a angular velocity range of ±180°/s.

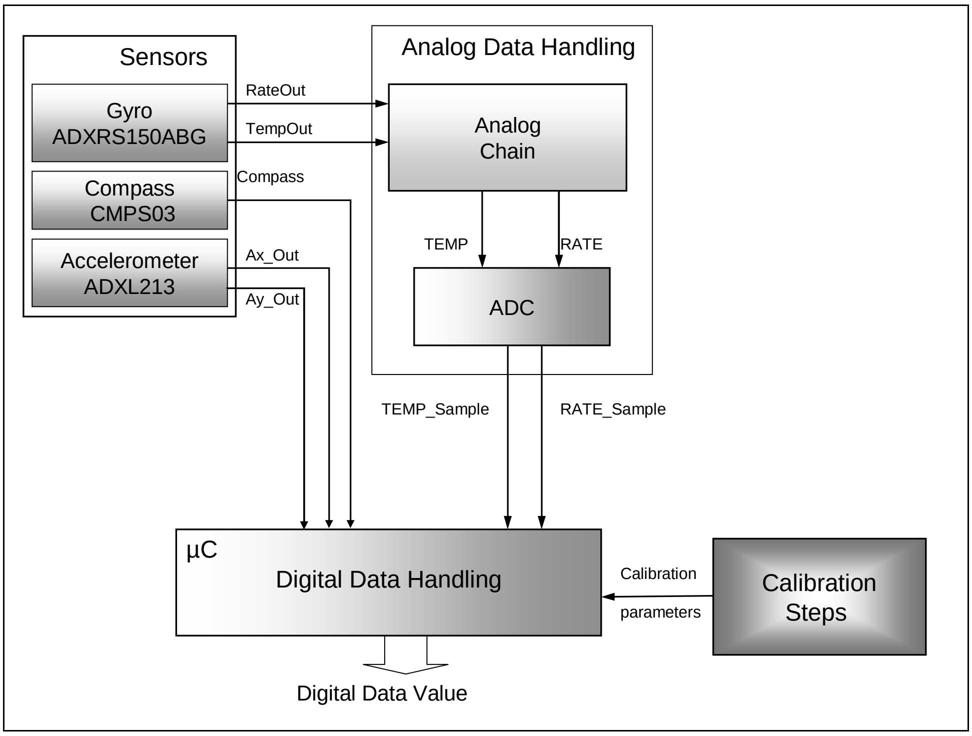


Fig. 6. 3 Sensors Acquisition Block Diagram

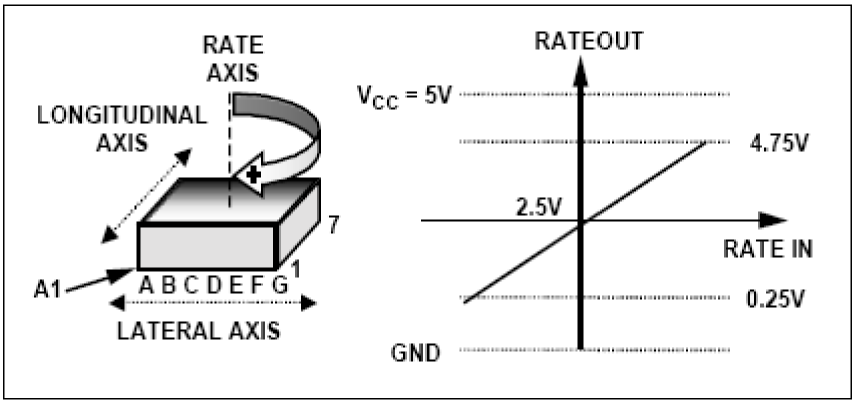


Fig. 6. 4 Voltage Output as a function of angular velocity

- a two-axes accelerometer ADXL202 (Analog, 1999): this provide two PWM output which duty cycle is proportional to the acceleration of two orthogonal axes. The maximum range of the acceleration detected is ±2g. In Fig. 6. 5 is shown the PWM output and the axes orientation of the accelerometer.

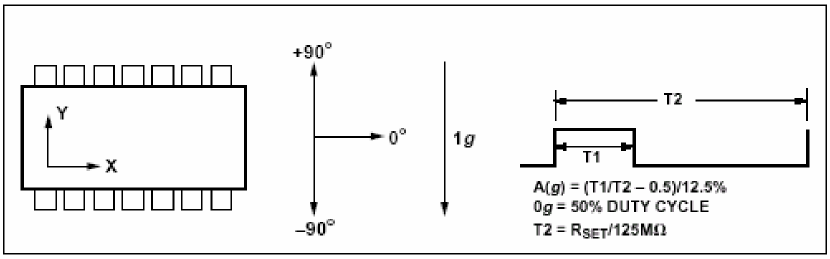


Fig. 6. 5 Axes orientation and PWM output

- a compass CMPS03 (Robot, 2007): this provide a PWM pulse output which pulse width is modulated with the positive width of the pulse representing the angle. The pulse width varies from 1 ms (0°) to 36.99 ms (359.9°). The angle value is related to the Magnetic North. In Fig. 6. 6 is shown the compass output referred to different orientations.

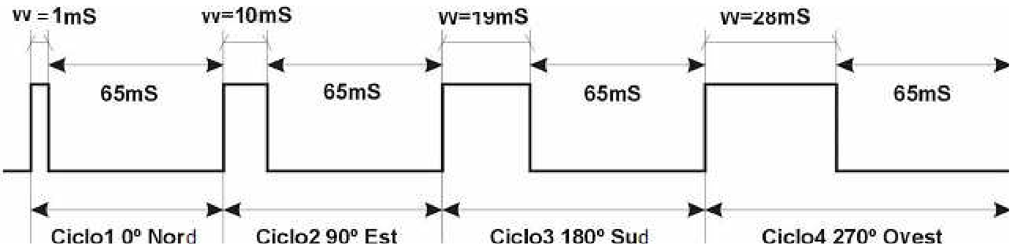


Fig. 6. 6 Compass PWM output

The second block is the *Analog Data Handling Chain* which elaborates the sensor output and convert the analog raw sensor data to digital raw sensor data. Therefore this one is used like the gyroscope's analog acquisition chain.

The acquisition of the gyroscope handles of subtracting the offset (output voltage when the rate is null), and calculate the scale factor. In this manner the angular velocity detected can be calculated as:

$$\omega(t) = \frac{GyroOut - Offset}{ScaleFactor}$$ **Eq. 6. 6**

Concerning the electrical scaling need to interfacing the sensor to an Analog-to-Digital Converter, the output of the *Analog Data Handling Chain* must ensure:

- linear angular velocity: ±180°/s
- Offset: 1,65V
- Scale factor: 8.25 mV/°/s
- linear output range: [0.165, 3.135]

After the *Analog Data Handling Chain* the gyroscope offset is as that in **Errore. L'origine riferimento non è stata trovata.**.

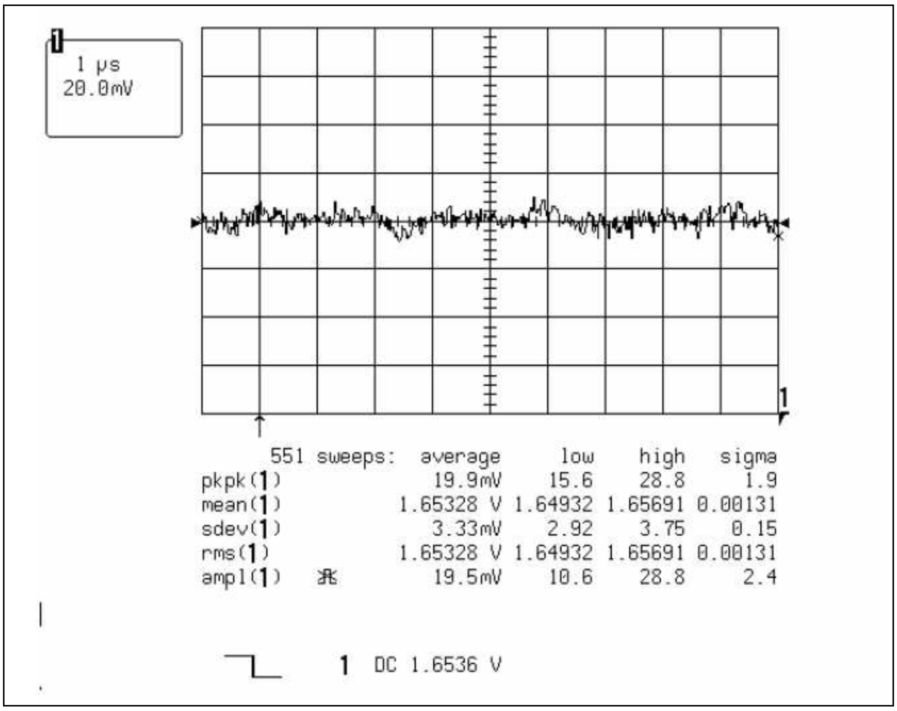


Fig. 6. 7 Gyroscope Offset

Fig. 6.8 shows the output voltage in a 180° rotation at an angular velocity of ±120°/s. The resulting scale factor is 8.24 mV/°/s.

Tha *Analog Data Handling Chain* of the gyroscope takes into consideration also the signal filtering to reduce the noise influence on the angular velocity measure. The cut off frequency has to be calculated depending on the application. If the output of the gyroscope is a sine function:

$$\omega(t) = \omega_{\max} \sin(2\pi f t) \quad \textbf{Eq. 6. 7}$$

where $\omega_{\max}$ is the maximum angular velocity detected to the gyroscope, the angular acceleration can be expressed as:

$$a(t) = \frac{d\omega}{dt} = 2\pi f \omega_{\max} \cos(2\pi f t) \quad \textbf{Eq. 6. 8}$$

The maximum angular acceleration is then:

$$a_{\max} = 2\pi f \omega_{\max} \quad \textbf{Eq. 6. 9}$$

The frequency of the gyroscope output signal is then proportional to the maximum acceleration:

$$f = \frac{a_{\max}}{2\pi\omega_{\max}} \quad \textbf{Eq. 6. 10}$$

The angular acceleration pattern can be utilized to dimensioning the filter. Fig. 6. 9 shows the slope of the angular velocity if it is performed a fast rotation around the centre of mass of the sensor.

In this case the maximum acceleration is:

$$a_{\max} = \frac{\Delta\omega}{\Delta t} = \frac{90.9}{84.5} \approx 1075 \quad \circ / s^2$$

The acceleration is proportion to a sine function with frequency of:

$$f = \frac{1075}{2\pi 90.9} \approx 1.9 \quad Hz$$

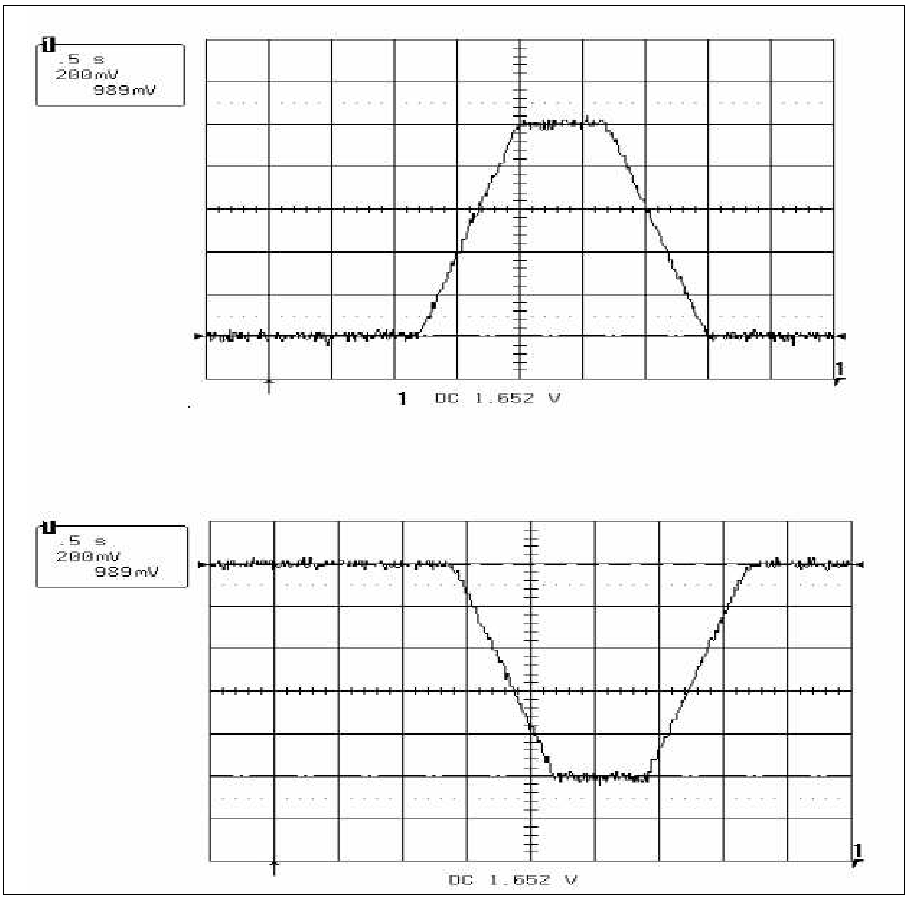


Fig. 6. 8 Clockwise and counter clockwise 180° rotation at angular velocity of ±120°/s

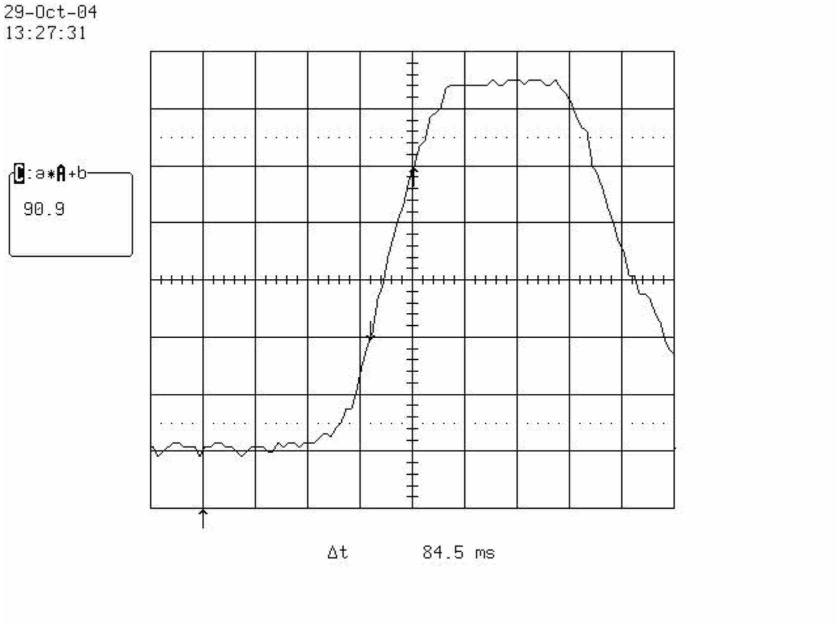


Fig. 6. 9 Angular velocity of fast rotation

If the experiment is repeated for other application (for example like a mouse) the maximum frequency of the gyroscope output is around 10 Hz. For this reason the cut off frequency of the filtering is imposed at 15Hz.

The third block is the *Digital Data Handling Acquisition Block* stored inside the microcontroller. This includes all the formulas that permit to convert *raw sensor data* to high level, interesting and usable data (*high level sensor data*). To do this calibration parameters are used. These are extracted from the *Calibration Block* by means of the calibration procedure as shown in the Paragraph 6.2. Now the *Data Handling Acquisition Block* of each sensor is investigated.

The acquisition of the gyroscope and temperature signals from the ADC are made at the same sampling frequency to simplify the implementation. Obviously this implementation is not efficient because the temperature varies slowly in comparison to the angular velocity. To reduce the loss of data while the microprocessor processes the gyroscope and the temperature value, they are used two data buffers loading alternatively with the temperature and the gyroscope samples.

The *high level sensor data* extracted from the *Digital Data Handling* are computed as in Eq.7.5.

The sensed acceleration is proportional to the PWM output duty cycle (Weinberg, 2009a). If T2 is the PWM output and T1 (Fig. 6. 10) is the high interval of the signal the duty cycle is:

$$DutyCycleX = \frac{T1x}{T2}$$
$$DutyCycleY = \frac{T1y}{T2}$$

Eq. 6. 11

In this way it is possible computing the duty cycle of the two signals by detecting the falling and the raising fronts of the outputs signals:

$$T1x = Tb - Ta$$
$$T1y = Td - Tc \qquad \textbf{Eq. 6. 12}$$
$$T2 = Tc - Ta$$

The acceleration for each axis (expressed in *g*) is computed using the following formula:

$$Acceleration = \frac{\frac{T1}{T2} - Offset}{ScaleFactor} \qquad \textbf{Eq. 6. 13}$$

where the *Offset* corresponds to the duty cycle to 0g (horizontal plane) and the *ScaleFactor* correspond to the variance of the duty cycle with respects to the variance of the acceleration. Both derives from the *Calibration Block***.** The proposed solution allows to have a new pair of acceleration value available every 16 ms and to compensate the jitter noise caused by the temperature on the PWM signal. Moreover, the division of the two temporal interval of the accelerometer signal allow to compensate the drift due to the temperature. In fact, the output component due to the temperature is elided in the division.

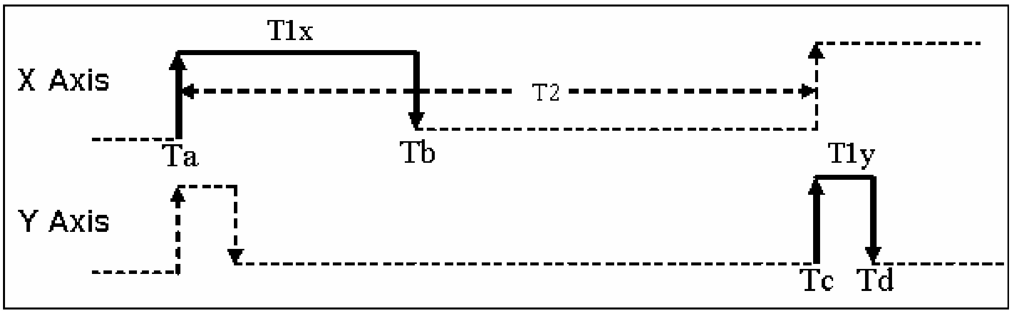


Fig. 6. 10 Accelerometer PWM output signal

The *high level sensor data* extracted from the *Digital Data Handling* are computed as in Eq.6.1.

The compass output signal is a PWM signal. Its square wave positive part has the temporal width proportional to the angle from the Magnetic North (Fig. 6. 6). The pulse width varies from 1mS (that coincide with 0°) to 36.99mS (that coincide with 359.9°). In other words 100uS/° with a +1mS offset. The decoding of the compass output is evaluated by measuring the width of the high pulse.

6.3 Sensor Calibration Procedures

As seen in the previous Paragraph, the conversion of *raw sensor data* to high level, interesting and usable data (*high level sensor data*), needs the presence of calibration parameter, which are extracted from the calibration procedures of the two sensors. In this Paragraph will be shown the procedure corresponding to the *Calibration Block*.

The calibration procedure of the two-axis accelerometer is necessary to extract the Offset and the Scale Factor of the sensor (Weinberg, 2009a). To calculate this values is sufficient to detect the output voltage of the two-axis only in two points (0° and 90°), which correspond to the acceleration of 0 g and 1g. In Fig. 6. 11 are shown the two steps of the procedure:

- first step: 0 g on the Y axes (*Ay_0*, correspondent to *Vy_0*) and 1 g on the X axes (*Ax_90*, correspondent to *Vx_90*)
- second step: 0 g on the X axes (*Ax_0*, correspondent to *Vx_0*) and 1 g on the Y axes (*Ay_90*, correspondent to *Vy_90*)

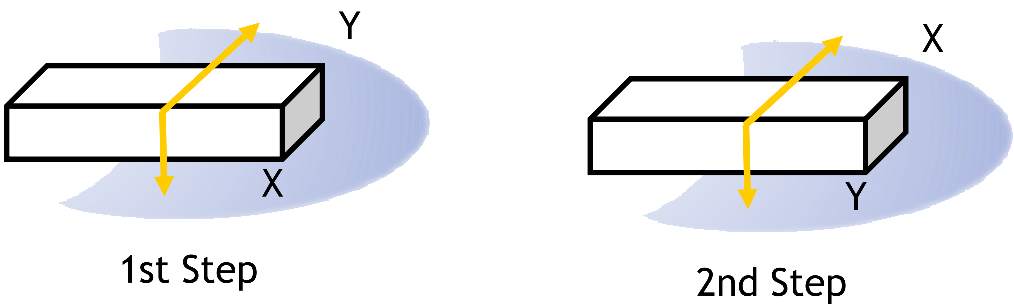


Fig. 6. 11 Accelerometer Calibration Steps

In this way it is possible to detect the characteristic line through which calculate the normalized current acceleration (*e.g. Ax*) starting to the current output voltage value (*e.g. VoltageX*):

$$Ax = (VoltageX - Ax\_0)\frac{Ax\_90 - Ax\_0}{Vx\_90 - Vx\_0} \qquad \textbf{Eq. 6. 14}$$

which is the line two-point form.

The calibration procedure of the one-axis gyroscope is influenced to the error source which this sensors are affected, as explained in Paragraph 6.1 (Woodman, 2007), (King, 1998). To take into account this errors, calibration procedure are performed. There are several methods to calibrate the gyroscopes depending on the source of error to take into account: in (Aggarwal, 2008), a six position calibration method is applied to estimate the deterministic errors of a gyroscope, characterizing all the noises of the sensors; (Chung, 2001) a procedure which considers the non-linearity in the scale factor and the gyroscopes susceptibility to changes in ambient temperature is performed; in (Scapellato, 2005) is proposed an in-use calibration procedure for gyroscopes.

As seen, the gyroscope output signal ($GyroOut$) is the composition of:

- a constant voltage, present also when the sensor is stationary (*Offset*)
- a voltage signal adds to the *Offset*, which varies proportionally to the angular velocity

In this manner, the output voltage $GyroOut$ can be seen as:

$$GyroOut = Offset + V\omega \qquad \textbf{Eq. 6. 15}$$

where $V\omega$=*ScaleFactor** ω*(t)*.

As seen, the output signal depends on the temperature and voltage supply variation. In particular, since the *Offset* value is equivalent to the *GyroOut* when the sensor is stationary, the dependency on temperature and voltage supply variation, can be highlighted on the *Offset* value:

Offset=Offset(Vcc, T).

The dependency on the voltage supply is managed through the filtering of voltage supply lines.

Concerning the dependency of the *Offset* to the Temperature, Fig. 6. 12 shows the *Offset* variation as function of the temperature. The output signal increases with increased temperature, but after the 58°, the characteristic is less steep. This fact suggests to approximate the function *Offset*(*Temperature*) with two straight line with different slopes, as shows in Fig. 6. 13. With this approximation the error for the two slopes (in the two different temperature range), remains very small (Fig. 6. 14).

To take into account this dependency, during the normal operation mode, the *Offset* has to be compensated in temperature. To do this for each output value, the equivalent *Offset* value, (which is utilized to calculate the *GyroOut* as in Eq. 6.15) is calculated as:

$$Offset(T) = \begin{cases} Offset(T0) + Ct1(T - T0) & T0 \le T \le T1 \\ Offset(T0) + Ct1(T1 - T0) + Ct2(T - T1) & T1 < T \le T2 \end{cases} \qquad \textbf{Eq. 6. 16}$$

where the following parameters are calculated through the calibration procedure:

- *Offset(T0)* is the *Offset* at the first temperature value of the calibration procedure (*T0)*;
- *T0*, *T1* and *T2* are, respectively, the first temperature value, the value of the temperature when the slope of the straight line changes, and the last temperature value of the calibration procedure
- *Ct1* and *Ct2* are the slopes of the two straight line.

The *Offset* calibration procedure extracts the above values maintaining the sensor still and stationary and varying the temperature.

Regarding the *ScaleFactor* calibration, the procedure consist of: rotating the sensor clockwise and counter clockwise of an angle of 360°. The sensor can be still. For each rotation it is detected the gyroscope output voltage in fixed temporal interval (each 120 ms). For each voltage value Fig. 6. 15:

- it is estimated the angular velocity utilizing the Eq. 6.15, in which the *ScaleFactor* is equivalent to the nominal value (*ScaleFactorNom)*
- it is computed the partial rotation angle utilizing the Eq. 6.4
-

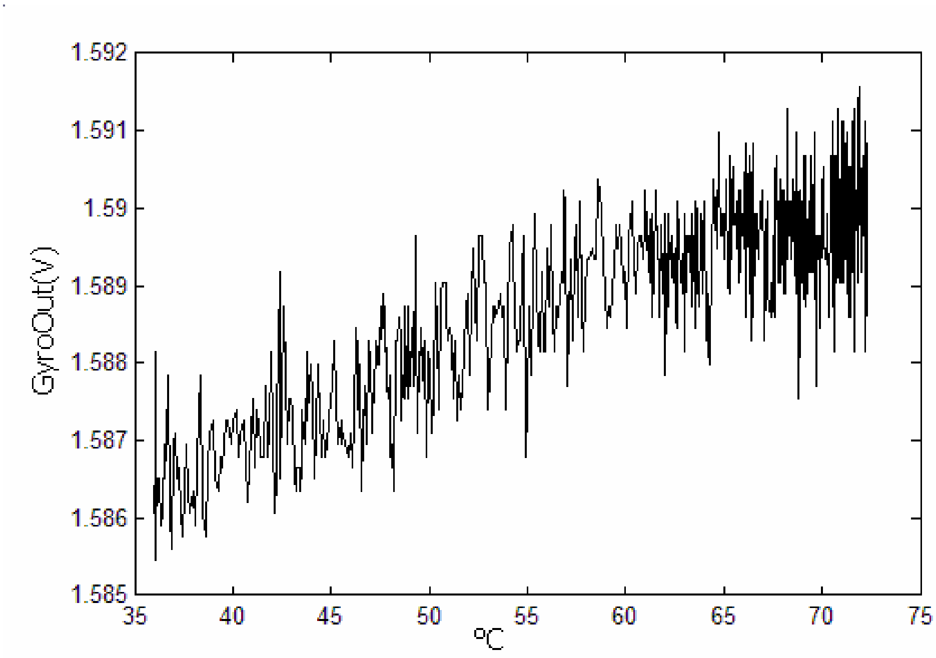


Fig. 6. 12 Gyroscope Output Signal vs. Temperature

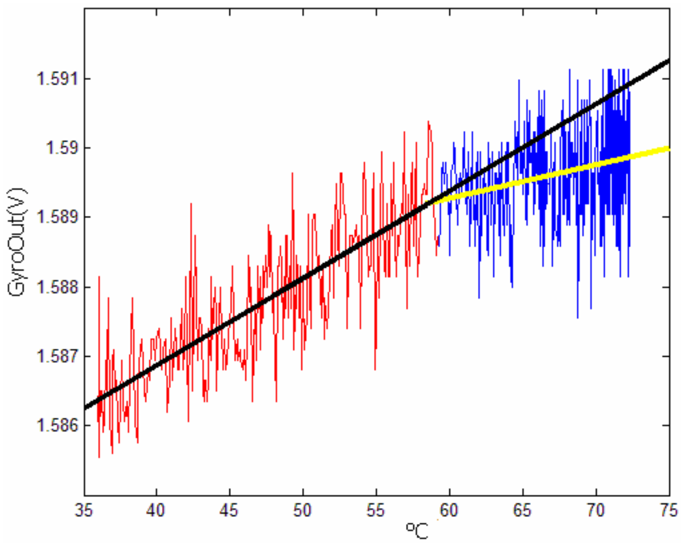


Fig. 6. 13 Gyroscope Output Signal vs. Temperature Linear Approximation

It is then calculated the total estimated rotation angle (*Yawtot*) and comparing to the real rotation angle (360°). The *ScaleFactor* is calculated utilizing a proportion:

$$ScaleFactor = \frac{Yawtot * ScaleFactorNom}{360}$$

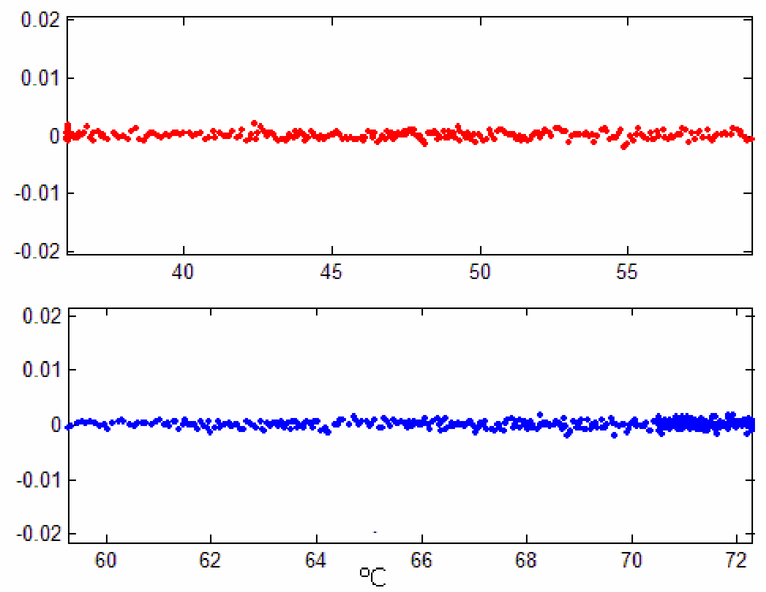


Fig. 6. 14 Approximation error for the two line

Theoretically the *ScaleFactor* does not depend on the sense of rotation, but the error sources introduce a misalignment. For this reason, two *ScaleFactor*, (one which is utilized when the gyroscope rotate clockwise and one which is utilized when the gyroscopes rotate counter clockwise), are computed and utilized to calculate $\omega(t)$.

This calibration procedure is convenient when precision table to rotate the gyroscope are not utilized. On the other hand, it has some drawback:

- the angular rotation is not imposed
- the rotation angle calculation is affected by the integration error
- the *Offset* value utilized to calculate $\omega(t)$ derived from its temperature calibration
- the synchronization between the temporal interval and the rotation is not guarantee. The *Yawtot* angle can be affected by error.
- It is proposed another *ScaleFactor* calibration, performed when precision table to rotate the gyroscope are present. The gyroscope is rotated in clockwise and counter clockwise manner of an angle of 360°. The sensor can be still. The same procedure as above is performed, but it is not calculated the rotation angle. For each temporal interval it is computed the partial angular velocity as in Eq. 6.15 and compared to the real angular velocity.

The entire calibration procedure is schematized in Fig. 6. 16.

6.4 Data Fusion Algorithms

The mainly components of the software which manages the entire orientation system are:

- a block which manage the communication with the hosting device through a defined protocol
- a block which acquires the *raw sensor data*, as seen in the Paragraph 6.2
- a block which computes, synchronize and fuse *high level sensor data*.

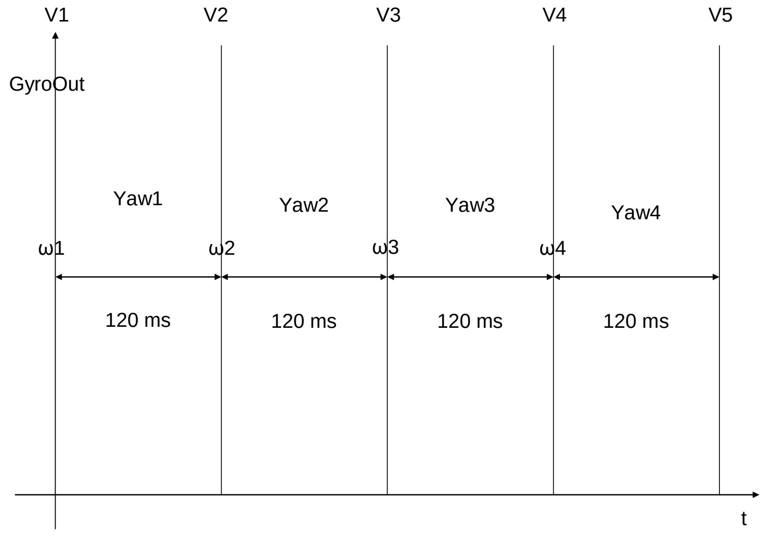


Fig. 6. 15 Gyroscope ScaleFactor Calibration

In this Paragraph it is expanded the latter block. The blocks structure is reported in Fig. 6. 17. It is important to notice the fact that all the sensor data have to be synchronized with each other.

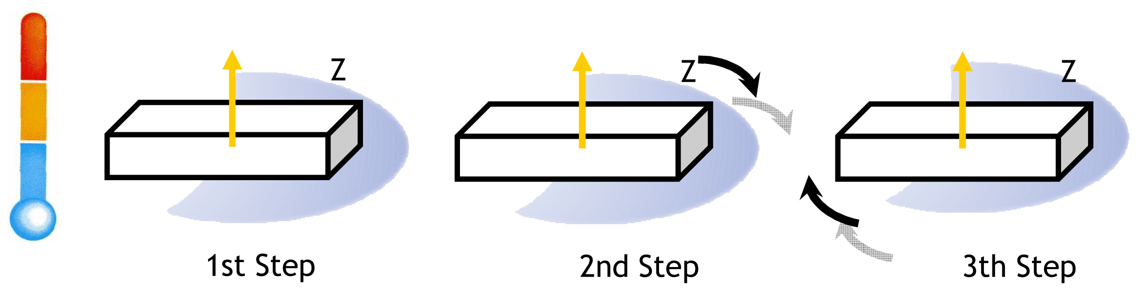


Fig. 6. 16 Gyroscopes Calibration Steps

Usually, *fusing* sensors data require to use complicated and computational heavy algorithms, *i.e.* Kalman filters (Yang, 2004; Roetenberg, 2005; Retscher, 2007), Particle filters (Fox, 2001). Appling such filters require to model the system and to determine the coefficients of the model, *i.e.* covariance of measures and errors. Furthermore, this filters introduce a delay in the elaboration of *fused* data.

In the case of the examined Multi-Sensor system, it was developed ad-hoc fusion algorithms aimed to:

- estimate the inclination angles, as seen in Paragraph 6.1
- estimate the rotation angle around the Z axis (Yaw angle), as seen in the Paragraph 6.1, taking also into account the *tilt* compensation as in Eq. 6.5.
- *fusing* the Yaw data with the information retrieved from the compass module (Azimuth angle, *i.e.* orientation angle with respects to the North), to detect the absolute orientation of the system, called Heading

In Fig. 6. 18 is shown the scheme of the *fusing* algorithm. It is highlighted how the sensors data and *the high level data* are correlated:

- the inclination angles derived from the accelerometer is utilized to compensate the gyroscope and compass *tilt* error
- the Azimuth signal provided by the compass is utilized as initial orientation to determine the absolute direction (Jamshaid, 2005)
- the Heading is determined as a combination of gyroscope and compass, because the compass is affected by errors due to magnetic disturbance and the Yaw determination is affected to the integration error (Ladetto, 2002a; Jamshaid, 2005; Jwo, 2008; Borenstein, 2009)

Considering the former of the above points, in general, the problem of tilt estimation can be likened to the problem of how to extracts, the static and dynamic components from the sensed acceleration (Antsaklis, 2005). In fact, if the sensor is still, the accelerometer axes sense the static component and Pitch and Roll angles can be calculated. If the sensor rotates, the accelerometer axes are affected to the acceleration due to the movement. In Fig. 6. 19 is shown the Roll angle variation as function of the angular velocity if the accelerometer is constrained. The slope is a parabola. In fact the accelerometer measures a fictitious component, which depends on (Fig. 6. 20):

- the centripetal acceleration in the case of the Y axis
- the tangential acceleration in the case of the X axis.

As consequence, the Roll and Pitch angles when the sensor rotates, have a static components which depends on the inclination, and a dynamic components which depends on the angular velocity in this way:

$$DynamicRoll \propto r\omega^2$$ **Eq. 6. 17**

$$DynamicPitch \propto r\frac{d\omega(t)}{dt}$$

where *r* is the radius of curvature.

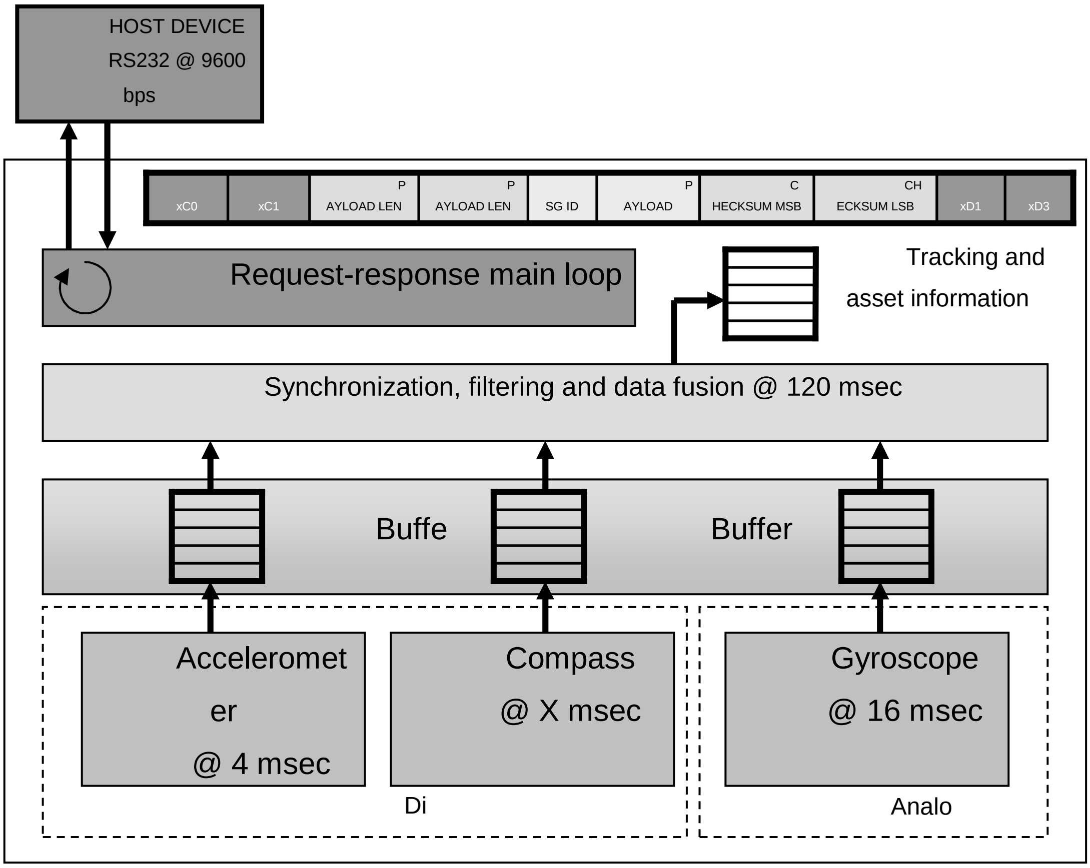


Fig. 6. 17 Software block diagram

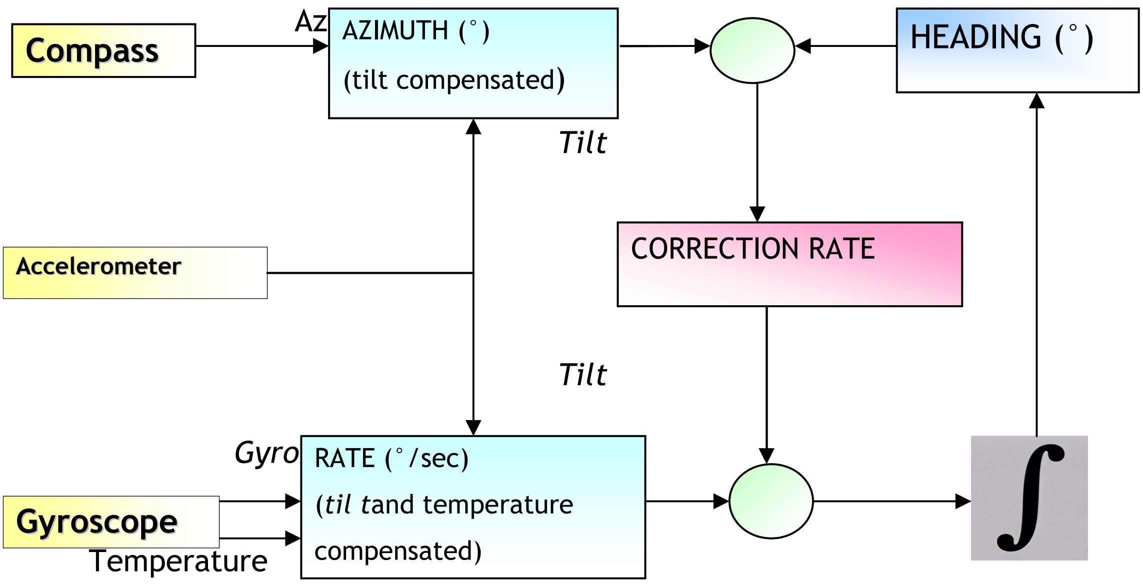


Fig. 6. 18 Conceptual schema of the heading system

This dynamic components influence also the Azimuth and the Rate, through the compass and gyroscope *tilt* compensation. To take into account this problem, a low pass filter was introduced only when the sensor is moving. However, this introduces a delay on the Heading detection.

The problem of the integration between the gyroscope and the compass to calculate the Heading, is solved by checking the presence of magnetic disturbance.

The proposed method sees the Heading value as the addition of the Yaw angle and a incremental value ($\Delta\alpha$):

$$Heading = Yaw + \Delta\alpha \qquad \textbf{Eq. 6. 18}$$

During the initialization procedure, the Yaw is set equal to zero and $\Delta\alpha$ is set to the Azimuth value (*alignment procedure*). During the normal operation mode the Yaw is calculated as in Eq. 6.4 and only if there are particular conditions on inclination and angular velocity, again the Yaw angle is set to zero and $\Delta\alpha$ is set to the Azimuth value. For this reason, a state machine is performed (Fig. 6. 21):

- State 0: the compass and gyroscope indications are reliable. The Heading value is computed as explained above;
- State 1: the gyroscope indication is reliable. The Heading value is computed as explained above;
- State 2: the compass indication is reliable. The Yaw value is imposed equivalent to the Azimuth angle;
- State 3: neither the gyroscope nor the compass indications are reliable. The Heading value is equivalent to the Yaw angle, but waits for a change of the state to reconstruct the real value.

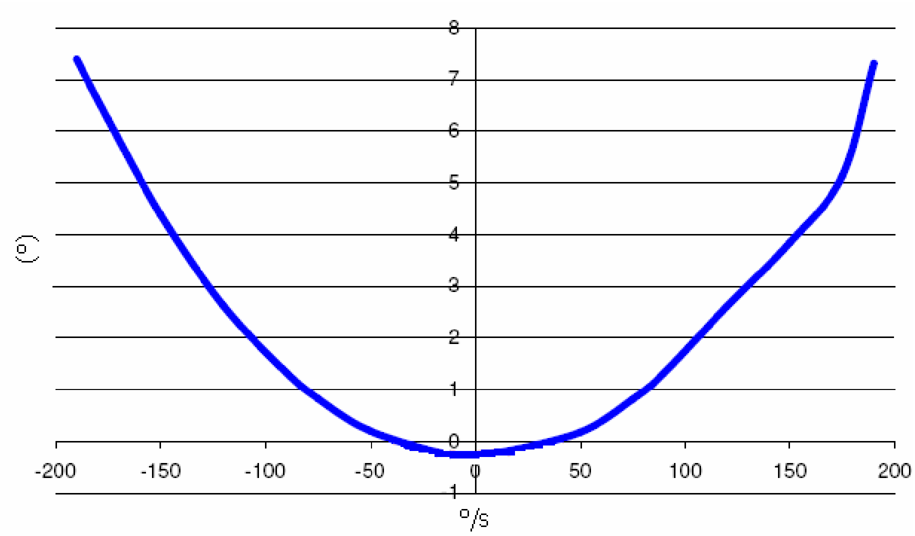


Fig. 6. 19 Roll dependency on Angular Velocity

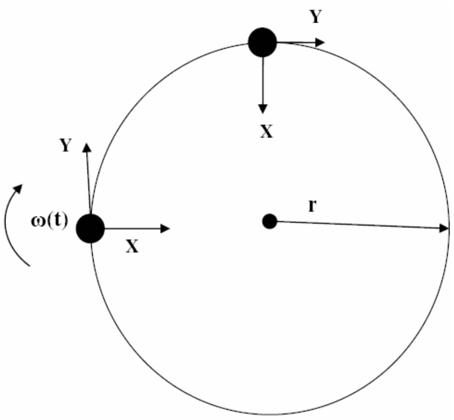


Fig. 6. 20 Effect of angular velocity on tilt

The transition condition are represented to values of angular acceleration or inclination angles for which the gyroscopes or compass output are not reliable:

- Tilt>10°, the compass output is not reliable
- ω>150°/s, the gyroscope output is not reliable
- Tilt>45° and ω>150°/s, neither the compass nor the gyroscope output are reliable.

It is important to notice that the *alignment procedure*, such as at the initialization, is performed every time the State returns on 0.

This algorithm is not optimal in fact:

- it does not take into account the integration errors due to the slow rotation of the gyroscope
- it does not take into account the possibility that, when the State returns to 0, soft iron interferences can perturb the Azimuth angle. The *alignment procedure* is in this case wrong
- it does not take into account the temporal integration drift on the calculation of the Yaw. In this case, static, temporal analysis of the gyroscope drift have to be performed in order to estimate a temporal interval, after the *alignment procedure*, in which the gyroscope output can be considered reliable. After that an *alignment procedure* has to be re/performed.

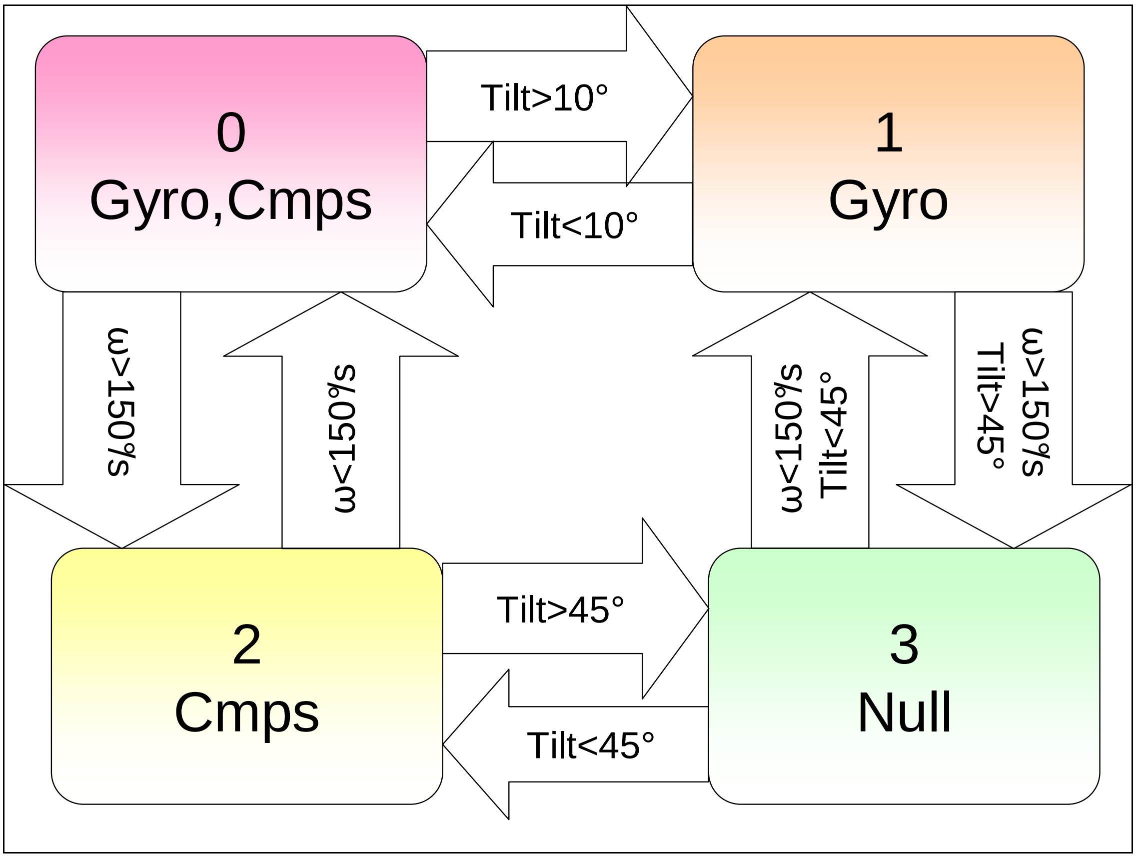


Fig. 6. 21 Compass-Gyroscope State Machine

Chapter 7

STATIC DIRECTION ESTIMATION USING A TWO AXES MAGNETIC SENSOR AND A THREE AXES ACCELEROMETER

In this Chapter is presented the second approach to estimating the orientation of a pedestrian user. This approach has been studied and developed in all its aspects, according to the Pedestrian Tracking System Requirement. The approach is based on a three-axes accelerometer and a two-axes magnetic sensor, whereby the user orientation in expressed as if she wearing a compass.

To begin, in Paragraph 7.1, rudiments of the theory of the Earth's magnetic field and the use of magnetic sensors as compass to detect the user orientation are shown. In Paragraph 7.2 are detailed choices regarding the hardware implementation of the system, according to the Infrastructure Independent Pedestrian Tracking System Requirement. Paragraph 7.3 and Paragraph 7.4 explains the innovative compass calibration procedure and the tilt compensation algorithm developed in the doctoral work.

7.1 Earth's Magnetic Field Theory and Magnetic Sensors

Magnetic fields (Campbell, 2003) are produced by the motion of electrical charges. The origin of the Earth's Magnetic Field is not completely understood, but it is thought to be associated with electrical currents produced by the coupling of convection effects and rotation in the spinning liquid metallic outer core of iron and nickel of the Earth. This mechanism is called the *dynamo effect*.

The effects of the EMF is approximately a magnetic dipole with the magnetic South pole near the Earth's geographic North Pole (True North) and the magnetic North pole near the Earth's geographic South Pole. The two magnetic poles are joined from an imaginary line (called *geomagnetic axis*) at an angle of 11,3° from the planet's axis rotation (Fig. 7. 1).

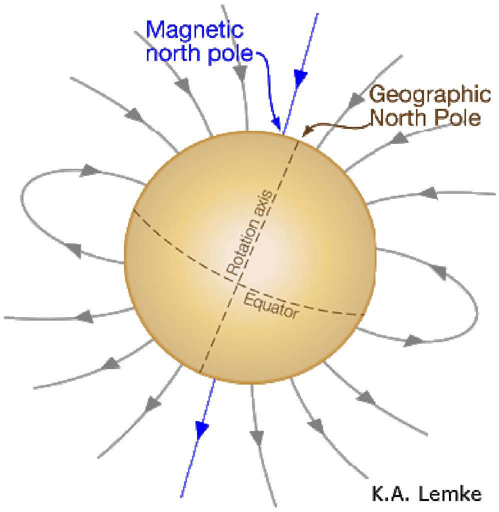


Fig. 7. 1 Model of the Earth's magnetic field

A compass needle dipped in the EMF follow the lines of force. Therefore it indicates one of the magnetic pole with an error that depends on the position on the Earth's surface. This error is called *magnetic declination* (Maus, 2009): it's the angle between the local magnetic field (the direction indicate from the compass needle) and the True north at any position on the Earth. The magnetic field for the year 2010 given by the 10th generation of the International Geomagnetic Reference Field is displayed in Fig. 7. 2 (Maus, 2009). It's required a declination angle compensation for long routes or near the poles. Otherwise, if the compass is used to detect pedestrian direction of movement, the declination angle compensation is pointless.

The total magnetic field strength and its Cartesian components can be measured by instruments called *magnetometer*. Anomalous values of these components are measured in some areas where magnetized rock or metallic materials are present. These generate weak magnetic fields which add up to

Earth's magnetic components. There are two different kinds of interference: *Hard iron* interference and *Soft iron* interference. *Hard iron* is caused by iron or steel which retains a high percentage of magnetism acquired. It acts like a magnet. *Soft iron* occurs when magnetometer is near to a ferromagnetic object.

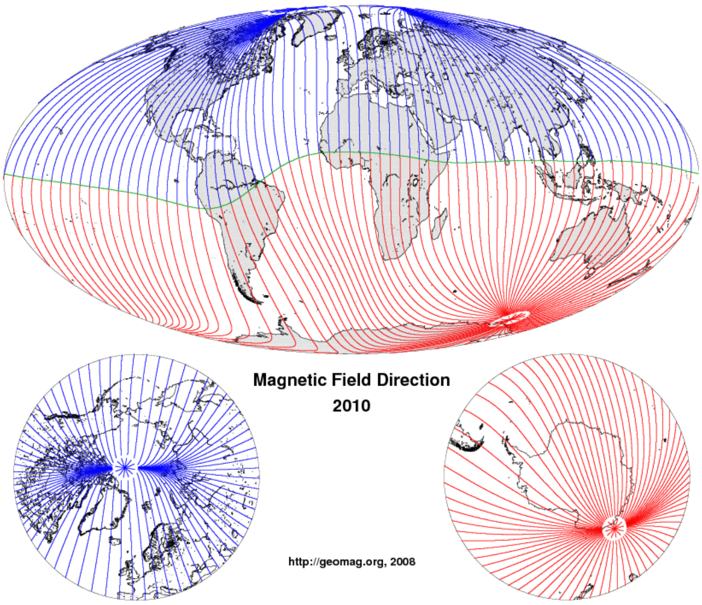


Fig. 7. 2 Magnetic Declination

The Earth's magnetic field can locally be defined by a vector (Fig. 7. 3) in which the *X* and the *Y* components are parallel to the Earth's surface and the *Z* component is directed toward the Earth's centre. In Fig. 7. 3 are given some definitions:

He: Earth's Magnetic Vector;

Heh: North Magnetic Vector, orthogonal projection of the **He** vector on the parallel plan to the surface;

Hex: *X* component of the Earth's Magnetic Vector;

Hey: *Y* component of the Earth's Magnetic Vector;

Hez: *Z* component of the Earth's Magnetic Vector;

Azimuth ψ: angle between the North Magnetic Vector and the movement direction (in clockwise mode), the computation is:

$$\text{Azimuth} = \arctan \frac{Hey}{Hex} \quad \textbf{Eq. 7. 1}$$

Dip Angle δ: angle between the Earth's Magnetic Vector and the horizontal plane, it is 0 to the equator and it is ± π/2 near the poles;

Declination Angle λ: angle between Magnetic North and True North.

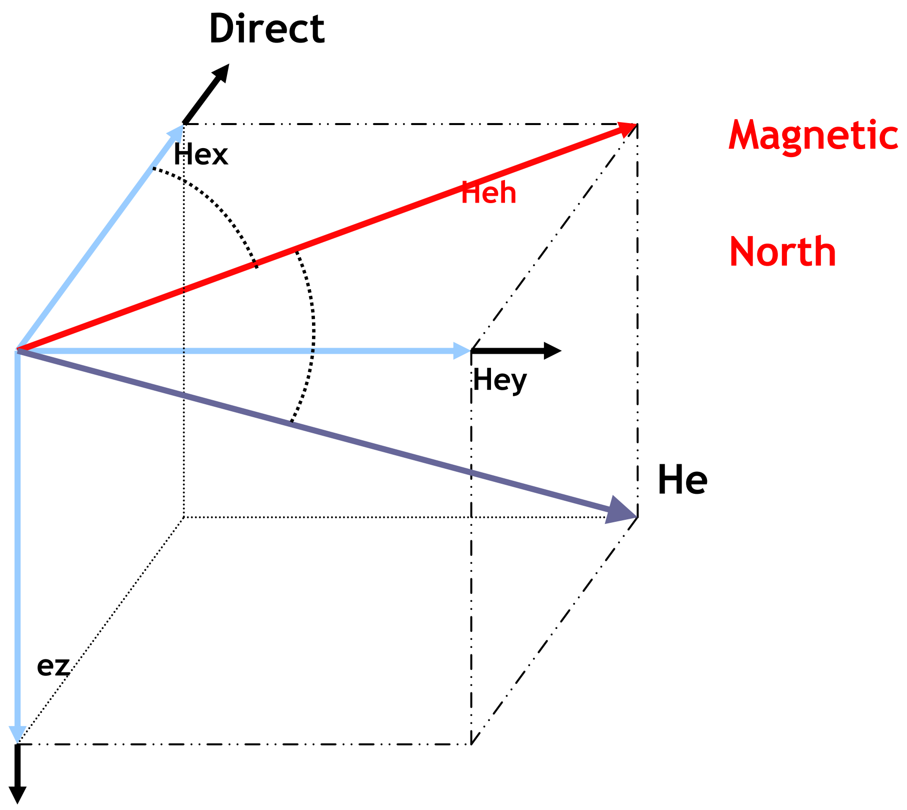


Fig. 7. 3 Earth's Magnetic Vector

There are several types of Magnetic Sensors: Fluxgate, Magneto-Resistive, Magneto-Inductive. A non-exhaustive list of this kind of sensors and an explanation about their behaviour is exposed in (Lenz, 1990; Caruso, 2007d) :

- *Fluxgate* Magnetic sensors (Steward, 2002): these magnetic sensors consists of an high magnetic permeability coil in which flows a periodical high intensity current. This brings the ferromagnetic core to work in the region of non-linearity. If the current flows in the two directions and the non-linear behaviour is presents in different way in this two cases, means that there is an external field superimposed. Another coil has an induced current equals to zero when the external fields are equal to zero, but different to zero when there are external fields. It is this induced current which is measured, and its value depends on the external fields. The fluxgate magnetic sensors have sensibility around 1mGauss. They are sensitive to shocks and they have a slow response to changes.
- *Magneto-Resistive* Magnetic sensors (Caruso, 2007a): these sensors are composed to thin stripes of Permalloy materials (alloy of iron, nickel, manganese and molybdenum with high magnetic permeability). This material varies its electric resistance depending on the magnetic field

applied. The magneto-resistive magnetic sensors have sensibility around 0,1mGauss and a response to changes around to 1 μs.

Appendix C presents a comparative analysis of some magnetic sensors.

Magnetic Sensors are utilized for different purposes (Caruso, 2007b) but their main use is like Direction Sensors, *i.e.* the computation of the Azimuth Angle, utilizing a reference system with X, Y and Z axes in relation to the magnetic axis. The movement direction (or *Heading*) will be along the X component. An introduction to the employment of the magneto-resistive sensor like *Heading Sensors* is shown in (Caruso, 2007a; Caruso, 2007c) .

A two axes Magneto-Resistive (MR) (Philips, 2000a) sensor was utilized in this PhD work. With this sensor it is possible to compute the Azimuth angle like in Eq. 7.1 . It is noteworthy that the trigonometric tangent is valid from 0° to 180° and that division by 0 are not allowed. As a result the following equations can practically be utilized:

$$\text{Azimuth} = \begin{cases} 90.0°(Hex = 0, Hey < 0) \\ 270.0°(Hex = 0, Hey > 0) \\ 180.0 - \arctan\dfrac{Hey}{Hex}(Hex < 0) \\ -\arctan\dfrac{Hey}{Hex}(Hex > 0, Hey < 0) \\ 360.0° - \arctan\dfrac{Hey}{Hex}(Hex > 0, Hey > 0) \end{cases} \qquad \textbf{Eq. 7. 2}$$

In all the cases it is necessary to determine the two horizontal component of the Earth's magnetic field Hex and Hey and add or subtract the declination angle. Thus the vertical component of the Earth's Magnetic Field is not utilized in the computation.

However, the discussion above remains valid only when the Magnetic sensor is perfectly parallel to the surface of the Earth at the point where the sensor is, *i.e.* perfectly horizontal. In fact, as shown in Fig. 7. 4 (where the sensor is tilted around the X axis), the magnetic sensor reveals an Y component with respect to its inclination (Hey') that is different from the horizontal one (Hey). In general the two horizontal components are affected by the vertical component of the field. As a result, the Azimuth computation is different from the horizontal case. The compass is said to be affected by a *tilt error* or non-horizontal error (Luczak, 2006).

Therefore, the use of magnetic sensors in dynamic applications, such as the tracking of users on foot (which is one of the aims of the doctoral work done), brings the need for compensation to eliminate the tilt error on Azimuth angle.

In this work an algorithm was chosen to compensate the *tilt error* presented in (Cho, 2005). This is based on the compensation of each compass component. For this reason it needs an estimation of the *tilt* third magnetic component (the missing third magnetic sensor axis). The following formulas show how the compensated Azimuth is calculated (Eq. 7. 3) utilizing the third magnetic component (Eq. 7. 4).

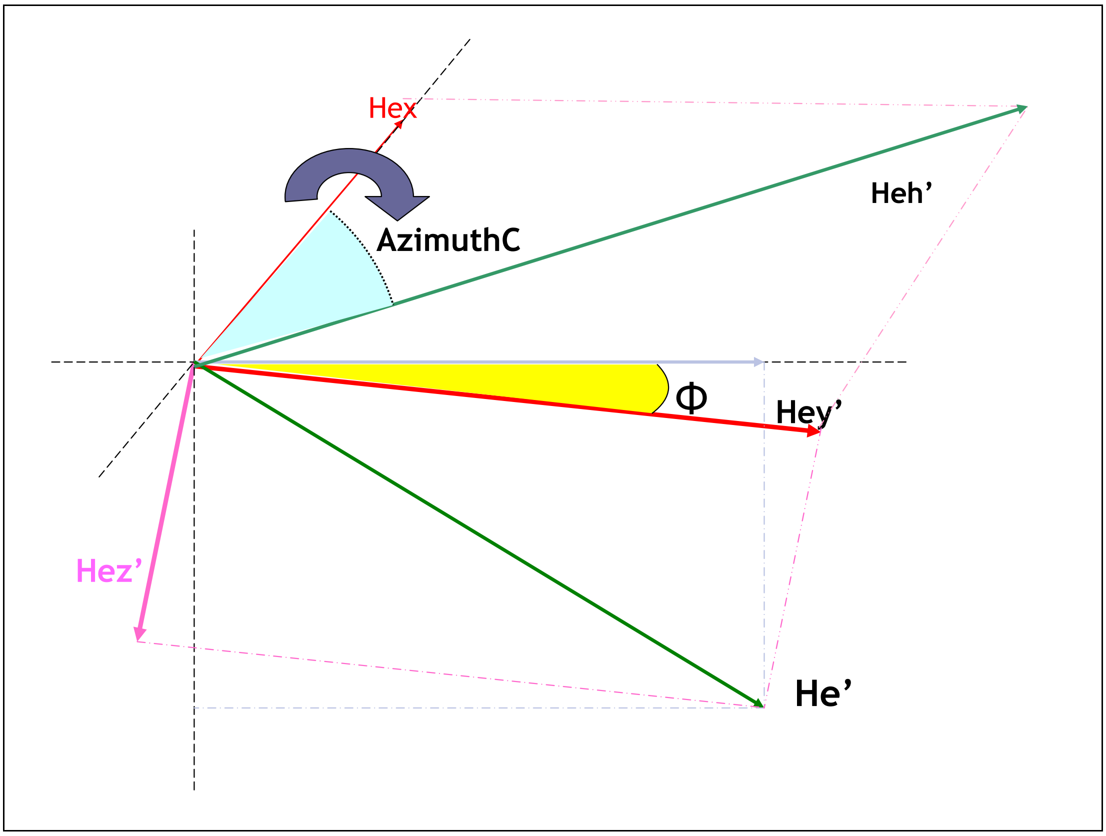


Fig. 7. 4 Azimuth computation affected by tilt error

$$AzimuthC = \arctan \frac{-\overline{Hey}'\cos\Phi + \overline{Hez}'\sin\Phi}{\overline{Hex}'\cos\Theta + \overline{Hey}'\sin\Theta\sin\Phi + \overline{Hez}'\sin\Theta\cos\Phi} \qquad \textbf{Eq. 7. 3}$$

$$Hez' = \frac{\sin\delta + \overline{Hex}'\sin\Theta - \overline{Hey}'\cos\Theta\cos\Phi}{\cos\Theta\cos\Phi} \qquad \textbf{Eq. 7. 4}$$

The algorithm will be explained in detail in Paragraph 7.4, but now it is important to note that the compensation needs the following parameters:

- δ: Dip Angle
- Φ and Θ: inclination angle (Fig. 7. 4)

In fact, a general inclination in the horizontal plane can be seen as consisting of two rotations:

- One rotation around the X-axis (inclination of the Y-axis), represented by the angle called *Roll* (Φ)

- One rotation around the Y-axis (inclination of the X-axis), represented by the angle called *Pitch* (Θ)

To calculate these angles it is well known in literature (as explained in Paragraph 6.1) that a 2-axes accelerometer can be utilized (Caruso, 2007a; Caruso, 2007c) with axes coincident with those of the magnetic sensor.

As you note the last parameter that remains to compute is the Dip Angle δ, which is found during calibration process.

In the following sections we shall see in detail how this issue has been solved and we shall see all the topics that allow the creation of a tracking system based on a heading computation.

7.2 Hardware System Architecture

This subsection discusses the architectural issues and their solutions for the creation of a infrastructure independent tracking system based on a two-axes compass sensor and a three-axes accelerometers.

The compass based tracking system developed for this PhD thesis consists of two parts: the Multi-Sensor-Unit (called *MSB5*) and the Power Supply and Communication Board (called *PS&Com*). The latter has already been explained in the Chapter 4 in the discussion about the Smart Object Power Managers (*SOPM*s). The first is in the heart of the tracking system because it contains the two sensors and it has been developed to meet the following criteria:

- Robustness to Electromagnetic Interference
- Low Power Consumption
- Wearability
- Usability:
  - User Feedback

From the integration point of view, one of the most important requirement in these systems is the Low Power Consumption. The *Range 1* SOPM module presented in the Paragraph (SOPM) is utilized, since the sensor unit posses the required load performance characteristics.

Fig. 7. 5 is the block diagram of power interface between the sensor unit and the SOPM module. It can be seen how the sensor module is equipped wih separate power supply in each of its sub-parts, with an independent power on/off signal. In this way each power supply is filtered.

Another precautions derives from the necessity to minimize magnetic fields disturbances, but bearing in mind the Wearability requirement. In fact, the primary objective of this sensor unit is to allow the knowledge of the user's orientation utilizing only a pack of sensors attached on the user. For this reason, from the developer point of view, the first decision is the position of the sensors pack. In this case the choice has fallen on waist sensor's pack. A need has therefore been to design a way to easily transport the sensors unit. Fig. 7. 6 shows how this problem has been solved. The figure on the left, shows how the elements of the system have been positioned: the sensor board is horizontal and supported by the box, the sensors with sensors facing upwards; the SOPM module perpendicular to the sensor unit to help support the first; the battery is attached to the cover of the box. The figure on the middle shows how the entire system appears when the enclosure is closed. The figure on the right indicate how the system can be worn by the user through a multi-pocket pouch.

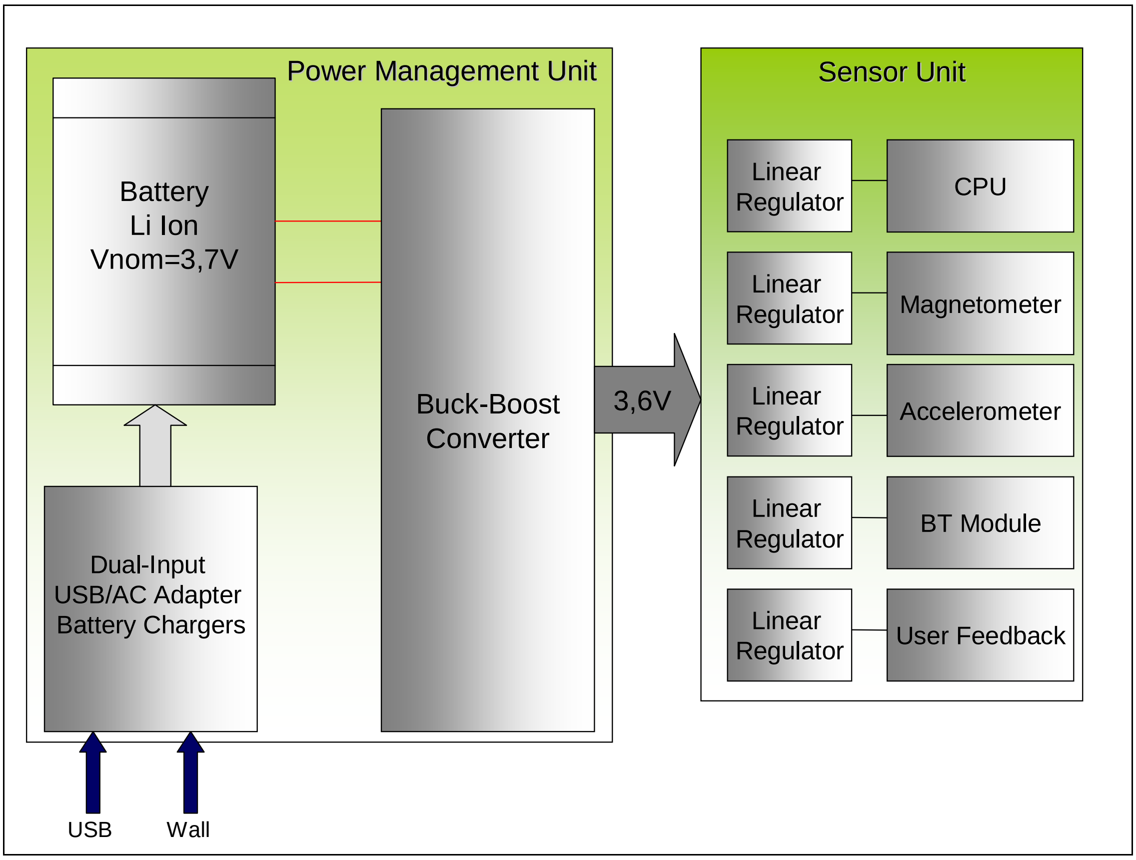


Fig. 7. 5 Sensor Unit Power Management

Fig. 7. 6 Pedestrian Tracking Unit form factor

The problem of the form factor is designed not only according to the Wearability requirement but also from the standpoint of minimizing magnetic fields disturbances. In particular, tests for the relative position of battery and magnetic component, have been made. To detect the position where the battery disturbs less the magnetic sensor, it was necessary to experiment on a range of 360°. This is because the Earth's magnetic vector can be influenced in different way for different orientation. The experiments concern on positioning the battery in different position relative to the magnetic sensor and rotating the magnetic sensor from 0° to 360°.Fig. 7. 7 indicate, for each considered position:

$$\int_{0}^{360} \left| ExpectedValue - ActualValue \right|$$ **Eq. 7. 5**

where the $ExpectedValue$ is equivalent to the value detected when the battery is not present. The lowest values of the integral occurs when the battery is perpendicular to the magnetic sensor and the opposite side to it (position 2 in Figure).

The influence of deterministic interference fields on a Magnetic Sensor can be assessed by inspection of a test diagram as shown in Fig. 7. 8 (Ng, 2009). The test diagram is a Lissajous figures (Ferréol R., 2004), yielded by a 360° rotation of the Magnetic Sensor and recording the Y output signals versus the X output signal. Without any magnetic interference, the diagram appears as a circle, having its centre at (0,0) and a radius equal to the magnitude He of the Earth field. All interference effects appear as a deviation from this shape. Basically, two kinds of interference can occur, called "hard iron effects" and "soft iron effects".

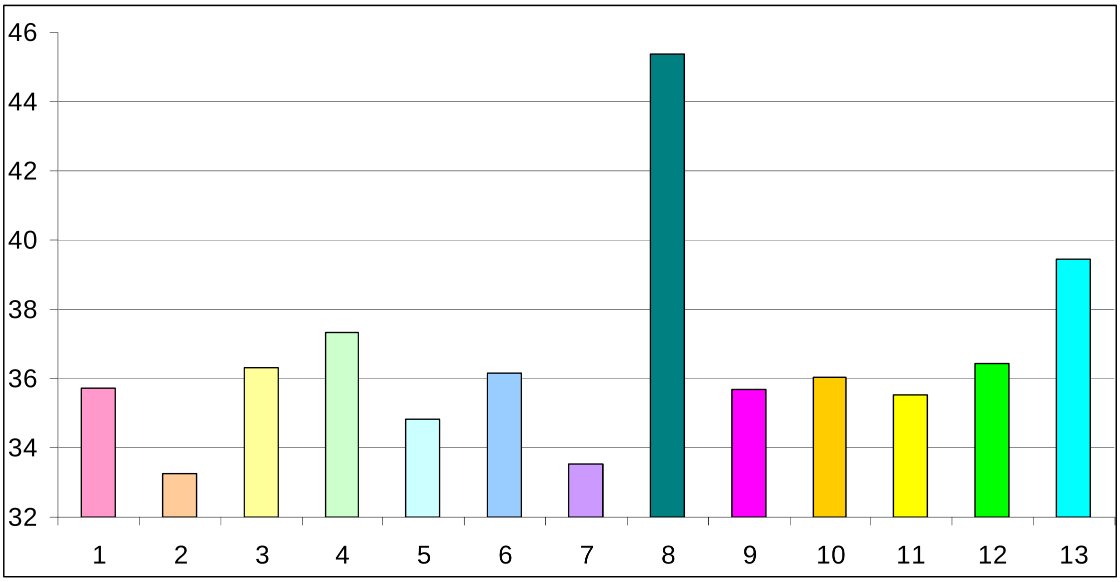


Fig. 7. 7 Integral of the deviation between the expected value and the actual value in a rotation of 360 °

"Hard iron effects" are caused by magnetized objects, which are at a fixed position with respect to the magnetic sensor. These generate a magnetic field, which is vectorially added to the earth field. Thus, in the test diagram this effect appears as a shift of the circle's centre to (H_{ix},H_{iy}), where H_{ix} and H_{iy} are the components of the interference field (Fig. 7. 9). "Soft iron effects" occur due to distortion of the earth field by ferrous materials. This effect is dependent on the orientation angle. Therefore, it appears as a deformation of the circle in the test diagram (Fig. 7. 9).

In Fig. 7. 10 is reported the Lissajous figure of the hard iron effect introduced by the presence of the battery (in the selected position) on the magnetic sensor. As you seen the slope is the same as the theoretical case, although the individual measures are wrong.

The first part of the system is Multi-Sensor-Unit. In Fig. 7. 11 the modular design of the sensor unit is exposed.

This comprises the following block:

1) User Feedback: according to the *Natural Interface* criteria (as in Chapter 3) two LEDs has been used controlled by the Micro-Controller utilized to give feedback (functional, spatial or temporal) to the user.

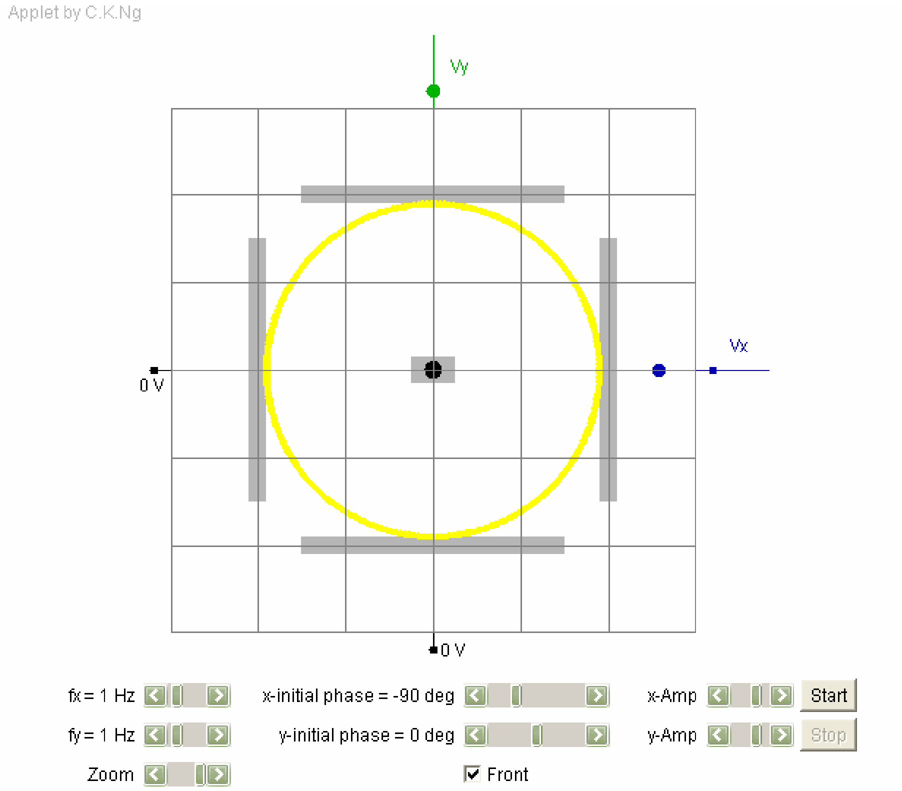


Fig. 7. 8 Lissajous figure

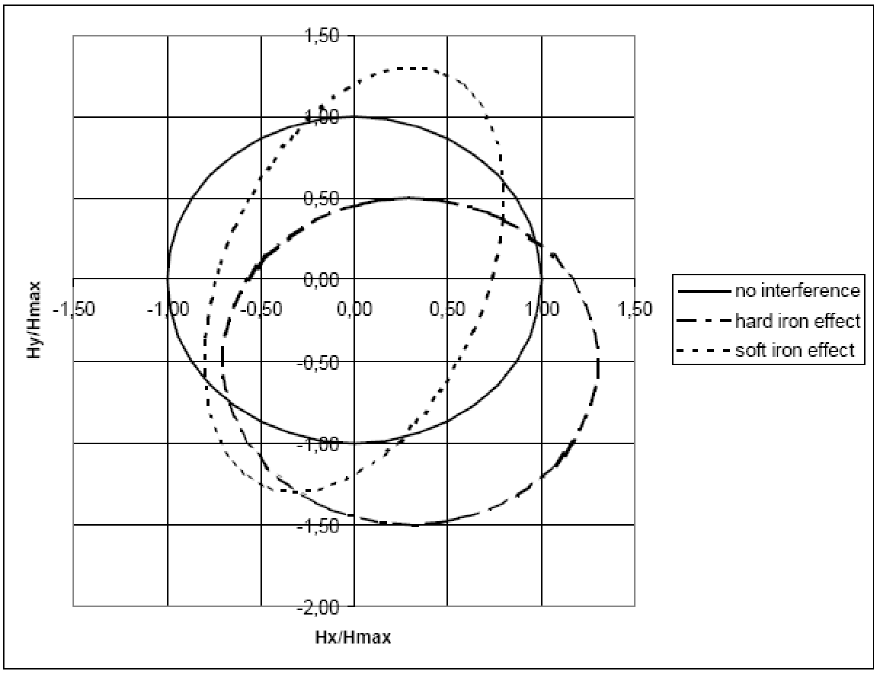


Fig. 7. 9 Effect of hard iron and soft iron effects on the test diagram

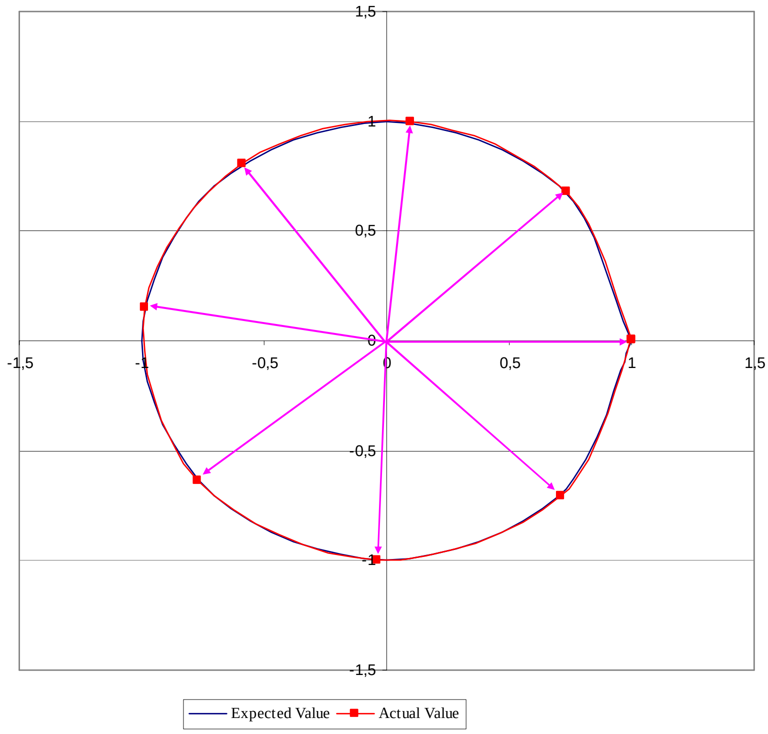


Fig. 7. 10 Hard Iron effect

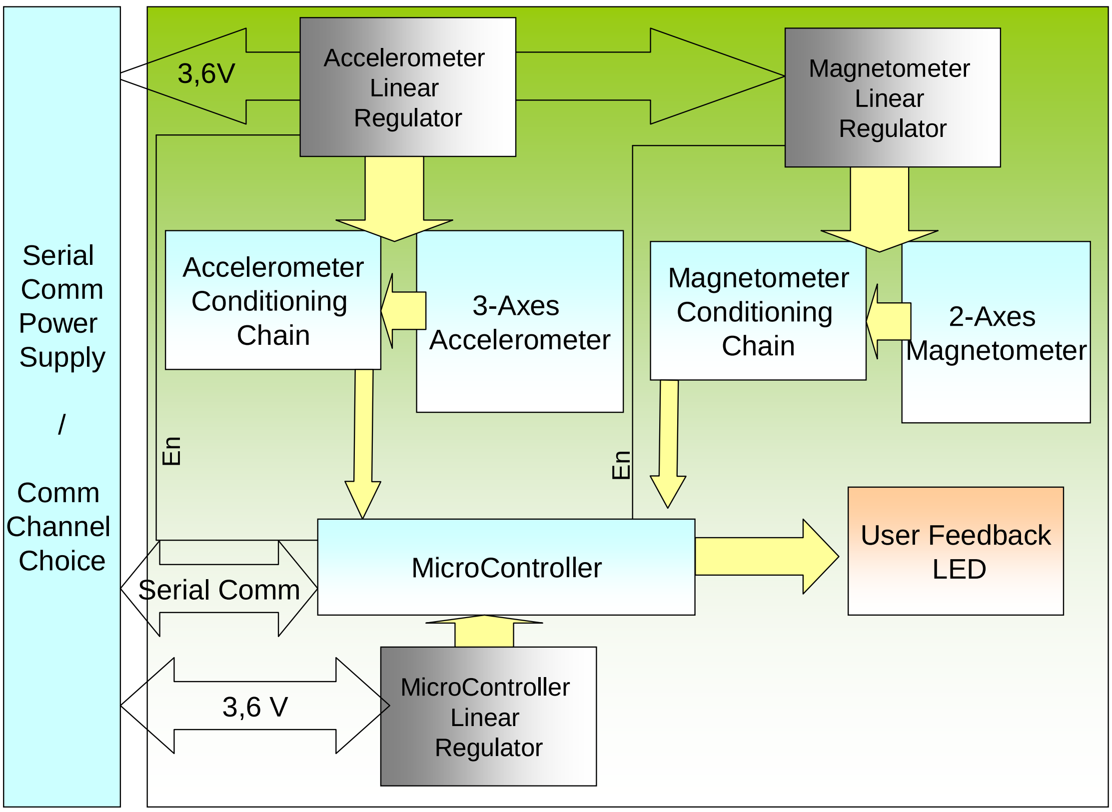


Fig. 7. 11 Multi – Sensor – Unit Block Diagram

2) Linear Regulator: Taking into account the quality criteria of low power consumption, low cost, and usability, for each sensor and part of the sensor unit, a power block has been added that convert the 3.6V sensor unit input voltage in the 3.3V voltage. It also allows the independent shutdown of individual parts and the reduction of electromagnetic interference. The function was achieved utilizing one low drop – out linear regulator TPS73633 (TI, 2008) for:

- The Three-Axes Accelerometer and its Signal Conditioning Chain
- The Two-Axes Magnetometer and its Signal Conditioning Chain
- User Feedback LEDs
- The Micro-Controller and its circuits

The use of this block leads to obtain a supply voltage with a peak-to-peak of 100mV ().

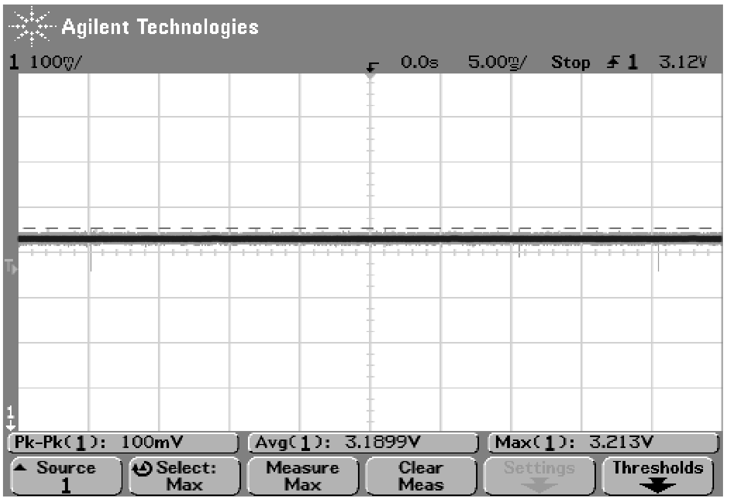


Fig. 7. 12 LDO output voltage

3) Micro-Controller: MSP430f149 (TI, 2004). “The Texas Instruments MSP430 family of ultra low-power microcontrollers consist of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low power modes is optimized to achieve extended battery life in portable measurement applications” (TI, 2009).

Its main characteristics are (in Fig. 7. 13 is shown the block diagram):

- Low Supply – Voltage Range, 1.8V . . . 3.6V
- 16 – Bit RISC Architecture
- 12 – Bit A/D Converter With Internal Reference, Sample-and-Hold and Autoscan Feature
- 60KB + 256B Flash Memory
- 2KB RAM Memory
- 125ns Instruction Cycle Time
- Two 16-Bit Timer_B With ten Capture/Compare Registers
- Serial Onboard Programming

- Fixed Point Arithmetic
- Ultra-low Power Consumption (Active Mode: 280μA at 1MHz, 2.2V)
- Package: QFN – 44

The direction of detectable acceleration are shown in Fig. 7. 14_b.

In the realization of the sensor unit (if the accelerometer is utilized as an inclinometer) the most important parameters are the answers analog axis versus the orientation of the sensor (). Note that the output range varies from 1.17V when the axis points to the Earth's surface (equivalent to an acceleration of -1g), and 2,13V when the axis points to the sky (equivalent to an acceleration of 1g). The average value (1.65V) is when the sensor is horizontal to the surface, *i.e.* the acceleration is 0g.

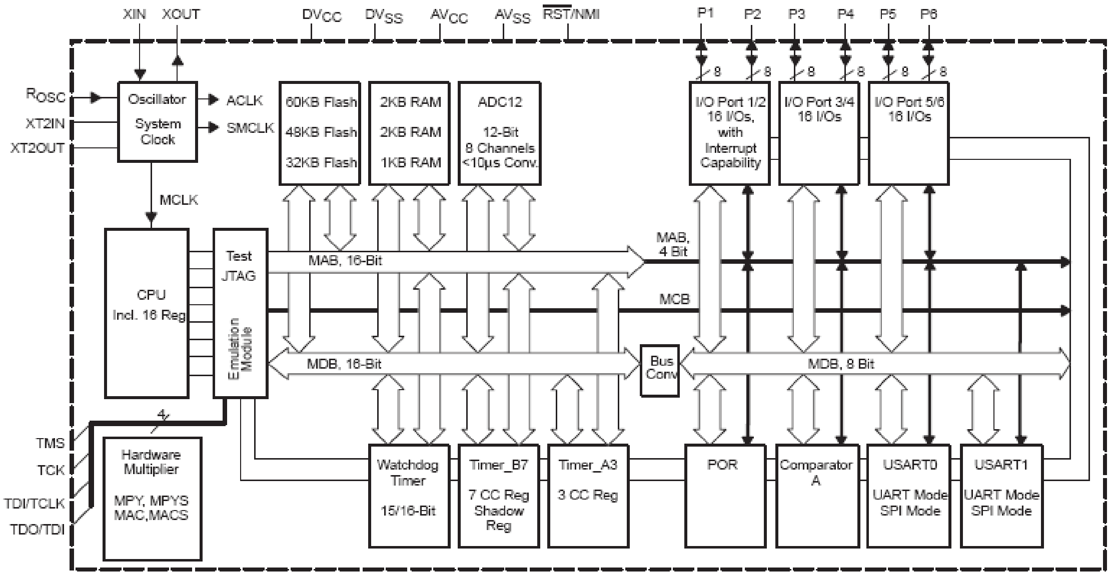
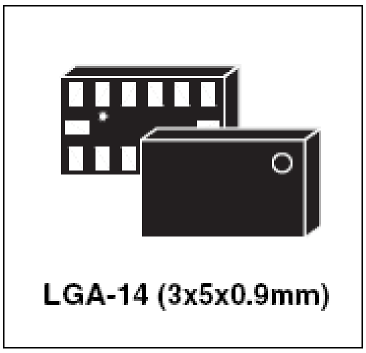
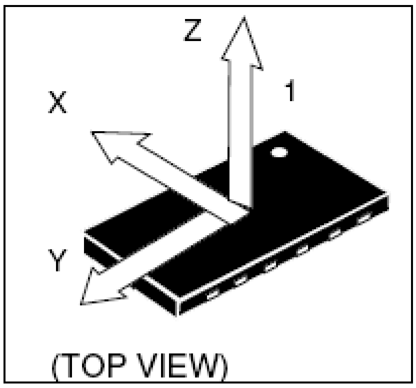


Fig. 7. 13 MSP430F149 Block Diagram





(a) **(b)**

Fig. 7. 14 LIS302SG Package (a), Axes Direction (b)

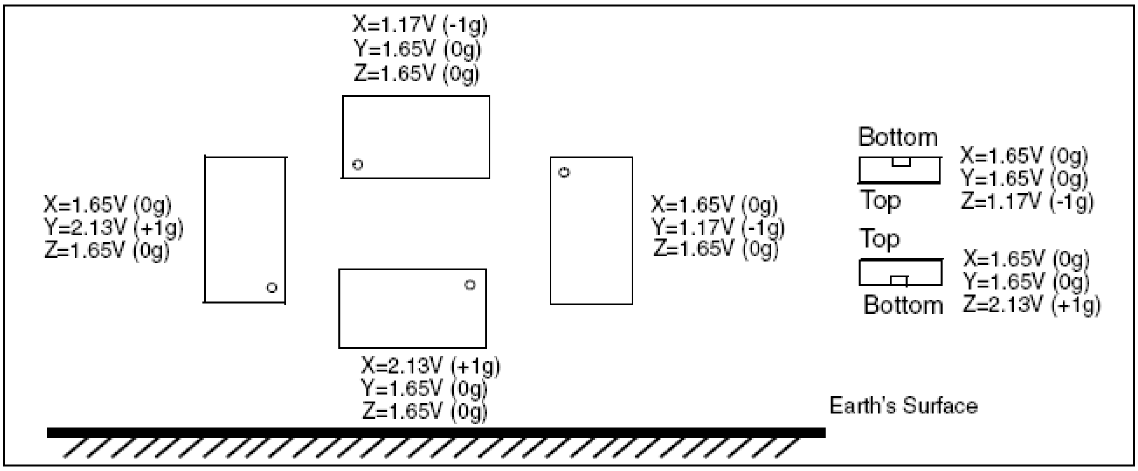


Fig. 7. 15 Output response vs. Orientation

4) Accelerometer Conditioning Chain: each Accelerometer axes need an analogic chain to adapting, filtering and converting the output signal in a signal suitable for acquisition by the microcontroller Analog-Digital Converter. This acquires signals that vary from 0 to 3.3V.

   The Accelerometer Conditioning Chain consists of:

   - Unit gain buffer amplifier
   - A low pass filter of second order Sallen-Key type with cut-off frequency of 24Hz. This frequency is trade off between the peak-peak of the output oscillations (which leads to an attenuation of 13dB at 50Hz) and the delay through the filter
   - A negative adder that subtract the output offset and amplify the signal (Fig. 7. 16). The output – input relation of this block is:

$$Vo = \frac{R_{16}R_{15} + R_{17}R_{15} + R_{16}R_{17}}{R_{16}R_{15}} - \frac{R_{17}}{R_{15}}Vcc \qquad \textbf{Eq. 7. 6}$$

The choice of the operational amplifiers utilized reflects the quality criteria about low power consumption and low cost application. The OPA2340 (TI, 2007) has been selected that is a rail-to-rail CMOS operational optimized for low-voltage, single-supply application and ideal for driving sampling ADCs.

For more implementation details please refer to Appendix A.

Utilizing these Conditioning chain the output signal for each axes is between 0.6V and 2.7V. The average value is 1.64V. Fig. 7. 17 shows the static output voltage. You can see that the peak-to-peak is 190mV, that is comparable to the supply voltage peak-peak.

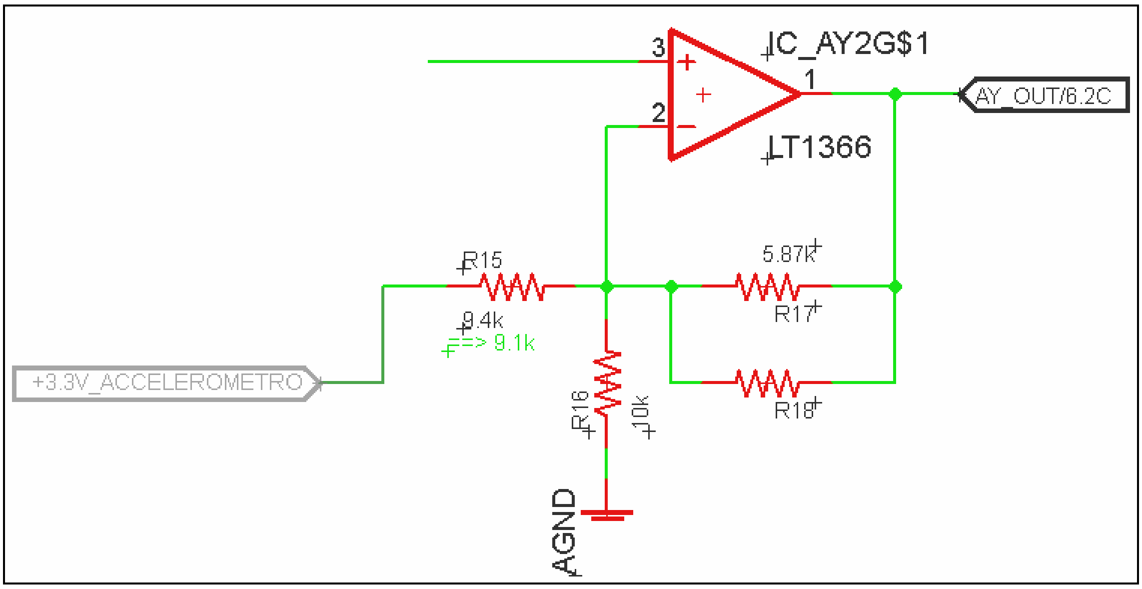


Fig. 7. 16 Negative adder of the Accelerometer Conditioning Chain

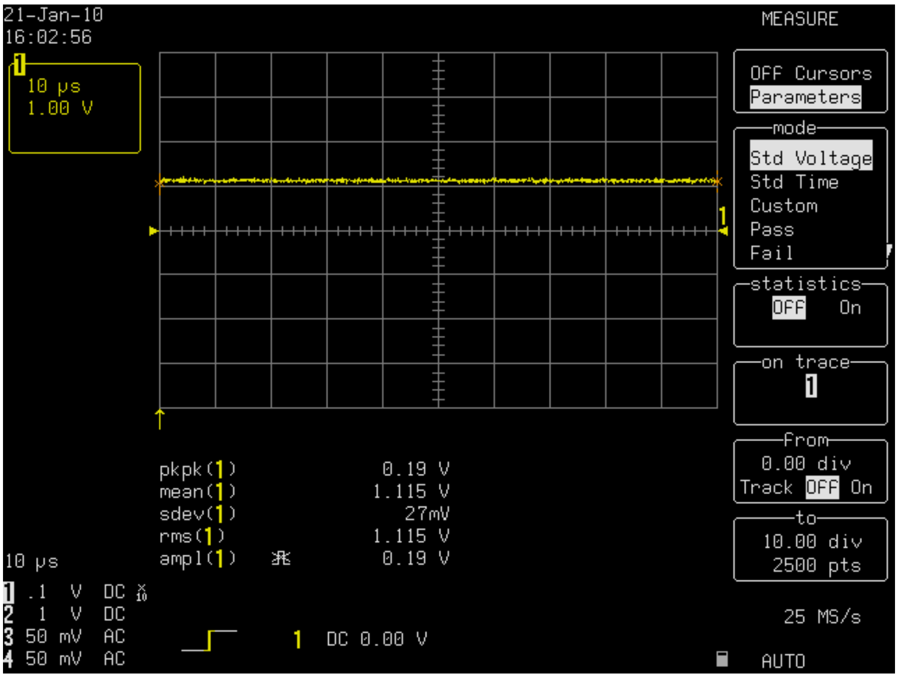


Fig. 7. 17 One Axes Accelerometer Output Chain

5) 2-Axes Magnetometer: KMZ52 (Philips, 2000b) “The KMZ52 is an extremely sensitive magnetic field sensor, employing the MR effect of thin-film permalloy. The sensor contains two MR Wheatstone bridges physically offset from one another by 90° and integrated compensation and set/reset coils. The integrated compensation coils allow magnetic field measurement with current feedback loops to generate outputs that are independent of drift in sensitivity.”

The main characteristics of the Magnetometer are:

- VCC bridge supply voltage: [3,2; 8] V
- Differential Output
- Total power dissipation: 130mW
- Maximum operating temperature: - 40 – 125°C
- Package: SO16

The axes orientation of the sensor is shown in Fig. 7. 18, where indicates the angle (α) between the external magnetic field (H), and the axes. If the angle α between the external magnetic field H and the long axis of the package is 0, H is along the most sensitive direction of die 2 (*i.e.* along the X axis) and perpendicular to the most sensitive direction of die 1 (Y axis). Otherwise, the magnetic field yields a differential output along X proportional to $cos(\alpha)$, and a differential output along Y proportional to $sin(\alpha)$.

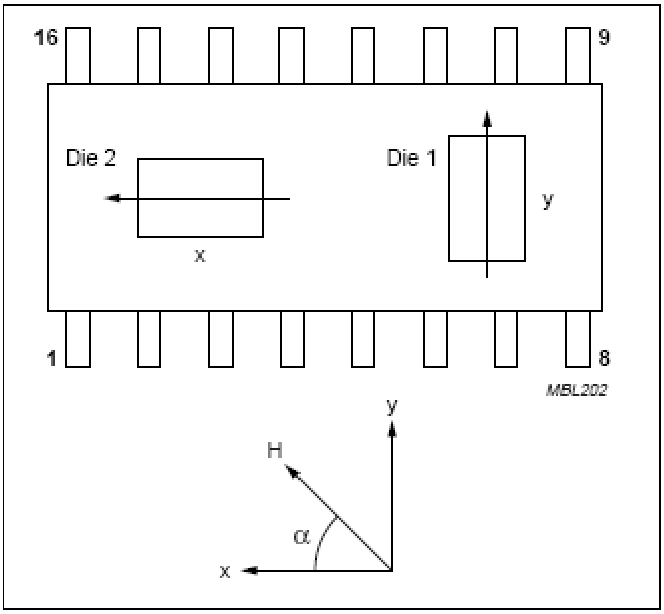


Fig. 7. 18 Magnetometer Axes Direction

This type of sensors are bi-stable: when they are subjected to a reversible magnetic field parallel to the magnetization, the direction its internal magnetization (and thus its characteristic, and the sensor output voltage changes polarity) is reversed or *flipped*. If the *flipping* is done repetitively, the desired output voltage will change polarity. However the offset voltage does not change polarity. This allows to compensate the sensor’s offset by means of an high pass filter.

Therefore, the voltage output is a differential square signal (VdiffOut in Fig. 7. 22).

The *flipping* is generated by applying alternately positive and negative current pulses to a set/reset coil of the sensor. To avoid loss in sensitivity, the current pulses should be short (only a few ms).

A 50 Hz clock signal (generated by the Micro-controller) is required for controlling the flipping source. Fig. 7. 19 shows how a current of 1.65A was created on the set/reset coil (which has an equivalent resistance of 4Ω) utilizing a 6.6V peak – peak voltage on C48.

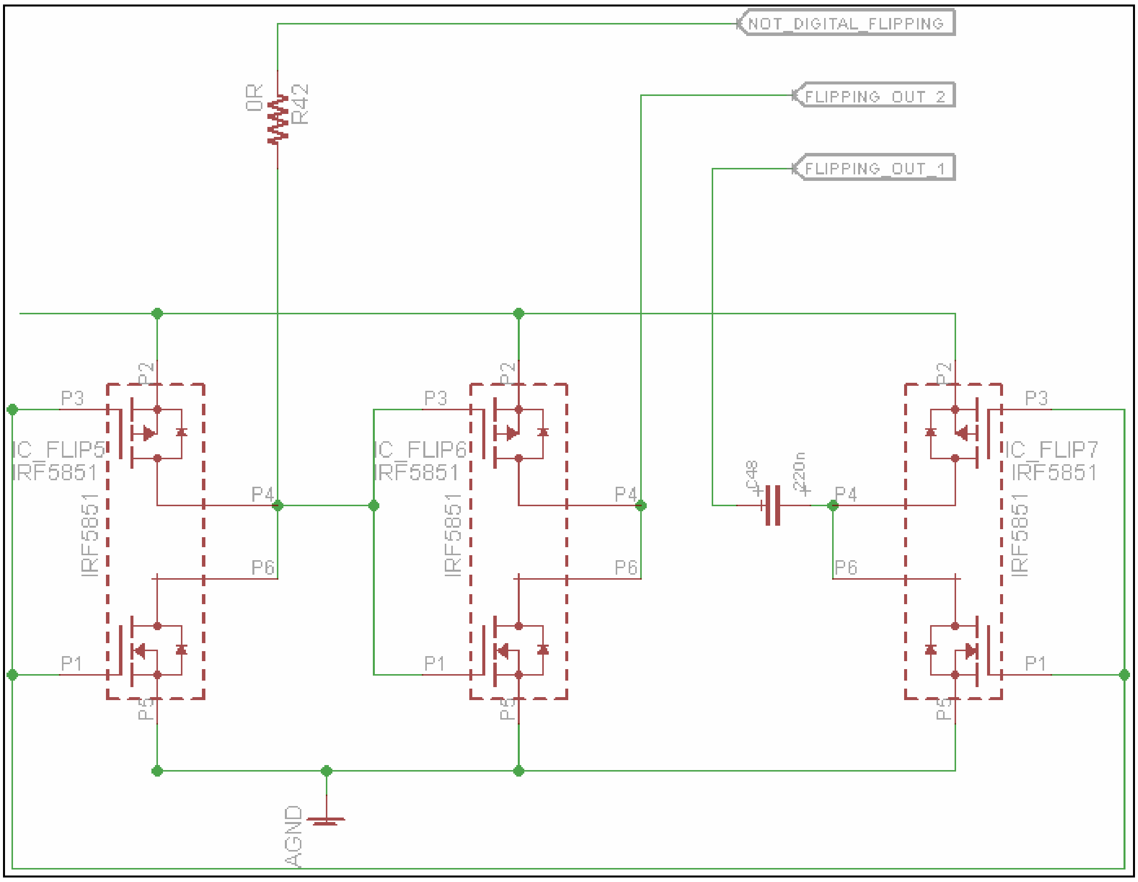


Fig. 7. 19 Flipping Generation Circuit

6) Magnetometer Conditioning Chain: each Magnetometer axes need an analogic chain to adapting, filtering and converting the output signal in a suitable signal suitable for acquisition by the microcontroller Analog-Digital Converter. This acquires signals that vary from 0 to 3.3V.

The Magnetometer Conditioning Chain (Stork, 2000) consists of:

- Adder and Integrator: this block (Fig. 7. 20) convert the differential output to single ended, amplifies the signal and removes the offset, integrating the signal and adding Vcc/2. In this way the magnetometer output voltages are positive square signals with frequency equal to the flipping one, and peak – peak amplitude proportional to the external magnetic field (VAdd in Fig. 7. 22).
- Rectifier: This block (Fig. 7. 21) compares the square signal obtained from the previous block and a square signal with frequency equal to the flipping one, but with Vdd/2 of amplitude, and in with phase opposite respect the flipping one (VNflip in Fig. 7. 22). This is

utilized to obtain a continuous voltage with average value of Vdd/2 and maximum value proportional to the external magnetic field (Vrect in Fig. 7. 22), performing an alternating +1 and –1 amplification, depending on the state of switch S1, which is controlled by the flipping generator.

- A low pass filter of second order Sallen-Key type with cut-off frequency of 24Hz. This frequency is trade off between the peak – peak of the output oscillations (which leads to an attenuation of 13dB at 50Hz) and the delay through the filter.

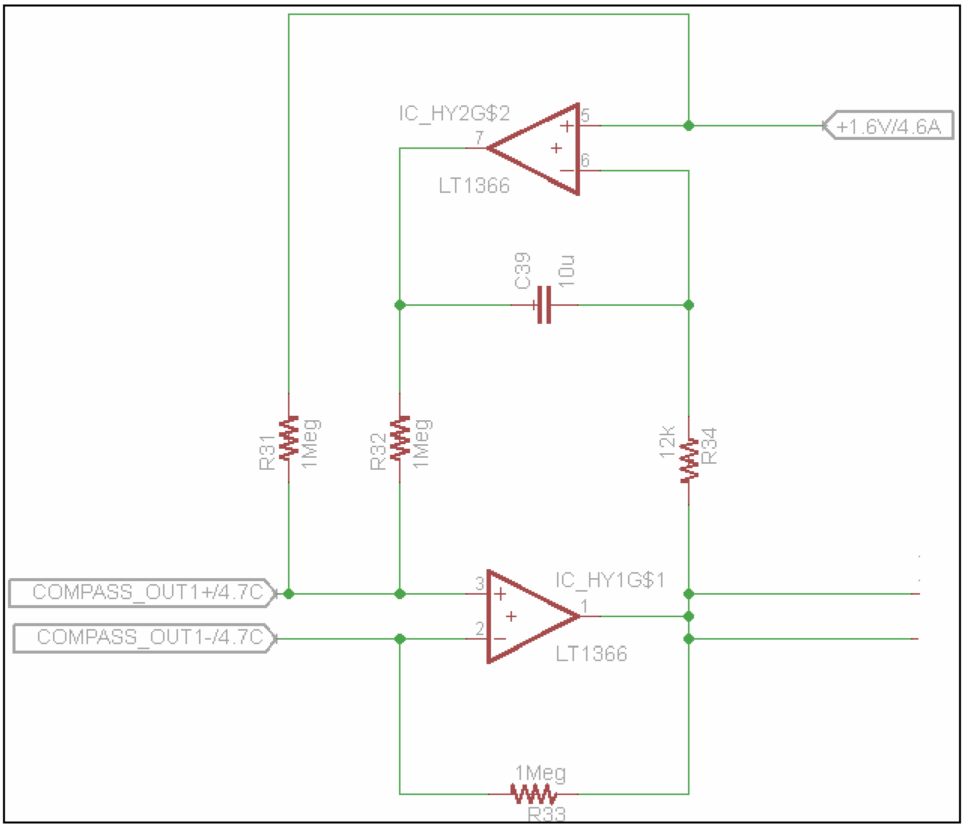


Fig. 7. 20 Magnetometer Adder and Integrator

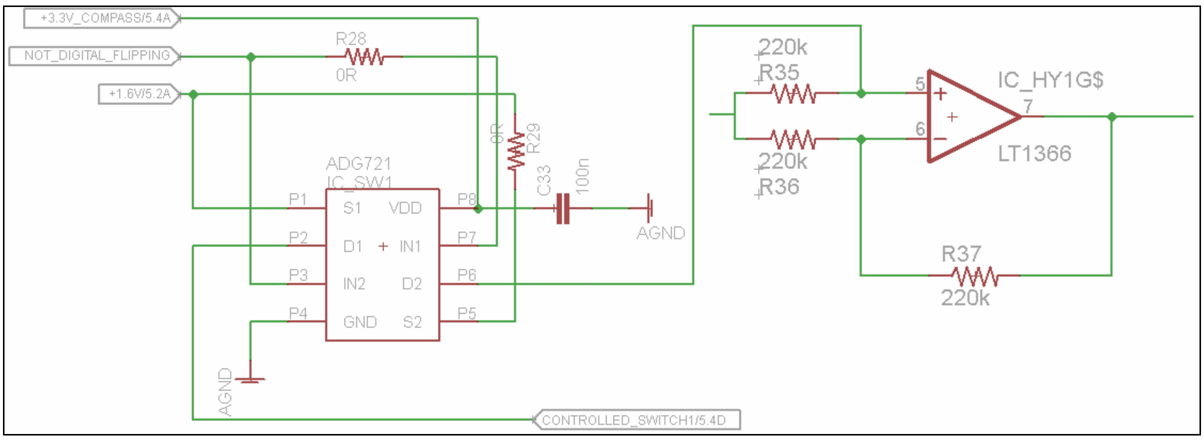


Fig. 7. 21 Magnetometer Rectifier

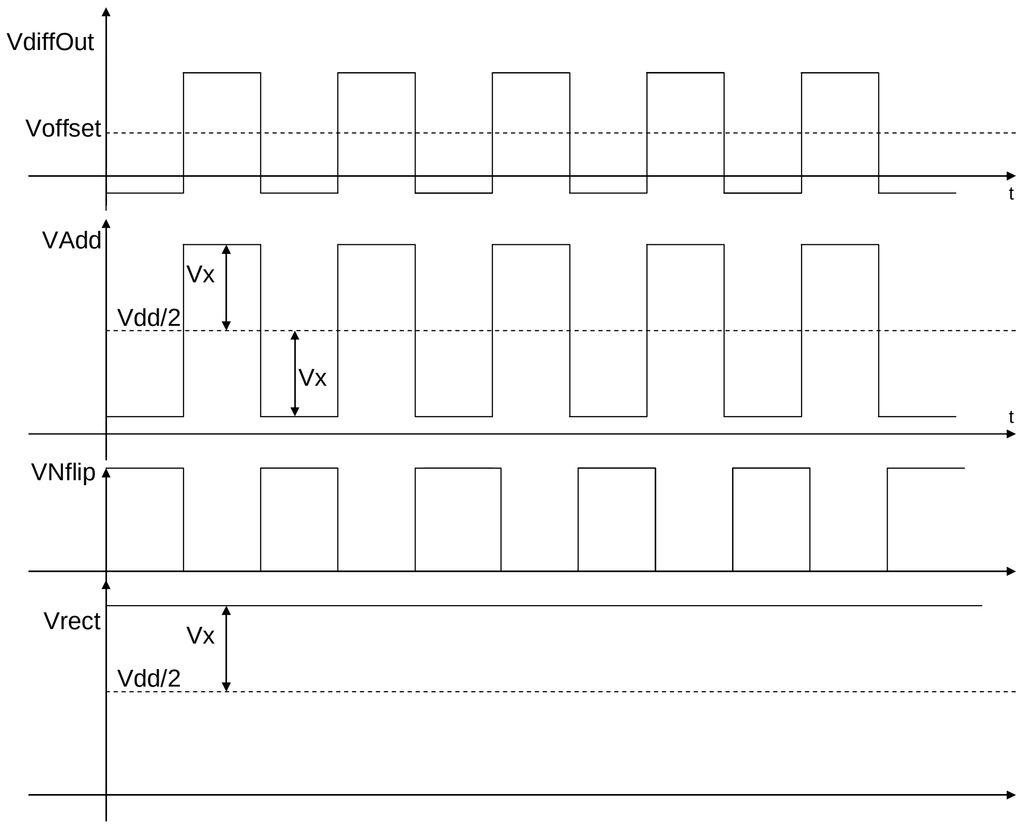


Fig. 7. 22 Magnetometer Signals Trend

For more implementation details please refer to Appendix A.

Fig. 7. 23 shows the static output voltage. You can see that the peak-peak is 220mV, that is comparable to the supply voltage peak-peak.

Another point taken into consideration in the implementation of the Magnetometer Conditioning Chain is the independence of the circuit topology with respect of the sensor mounted. Indeed, in this PhD work, it has been noted that the output characteristics of the 2-Axes Magnetometer KMZ52 varied depending on the sensor. This is always linear but changes the slope of the characteristic Vout(H). For this reason it has been chosen to maintain a fixed topology of the circuit and vary only the value of a single resistance (*R33*) to maintain the dynamic of the output signal of the Magnetometer Conditioning Chain intact.

As seen the influence of deterministic interference fields on a Magnetic Sensor can be assessed by inspection of a Lissajous figures (Ferréol R., 2004). The figure Fig. 7. 24 shows the Lissajous figure that relates the outputs of the X and Y Magnetometer Conditioning Chain yielded by a 360°, without magnetic interference. It can be seen how the relationship is a circle having its centre in (0,0).

In Appendix A can be seen in detail the schematics of the entire board.

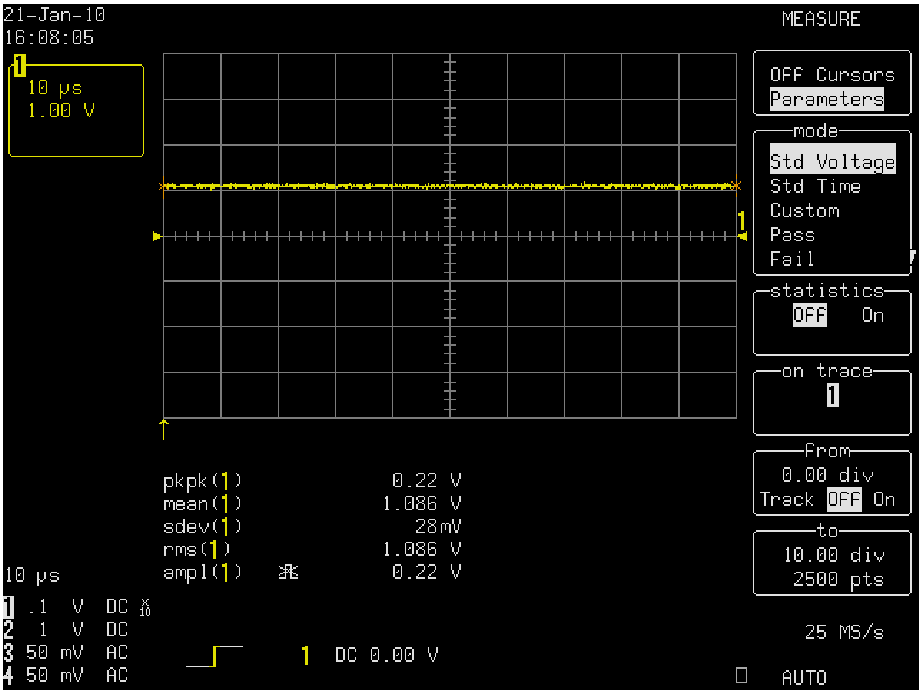


Fig. 7. 23 One Axes Magnetometer Output Chain

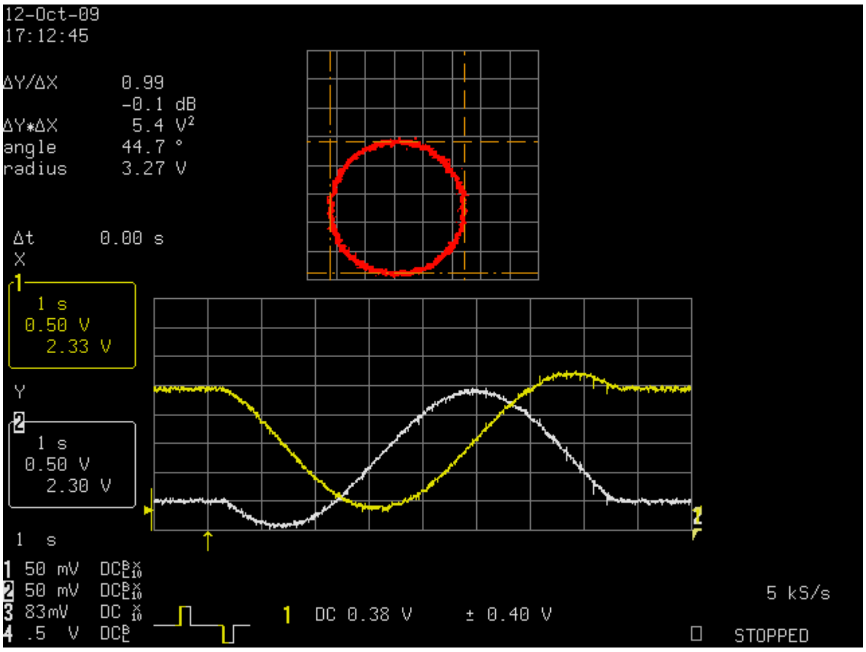


Fig. 7. 24 Lissajous figure of Hy/Hx output

The Multi – Sensor – Unit was realized in this PhD work in a board with this characteristics (Fig. 7. 25):

- Dimensions: 104.8 x 38 mm

- Number of layer: 4
- Type of components: through – hole and SMD
- Substrate type: FR4
- Substrate thickness: 1.6mm
- Copper thickness: 35um

In Appendix B it can be seen the layout of the board.

According to the quality criteria of low power consumption, test were done. Table 7. 1 lists the different power consumption (in mA) in different modes of operation (the Micro-Controller is always on).

User Feedback ON	7,3 mA
Flipping Circuit	7,7 mA
2 – Axes Accelerometer + Conditioning Chain	54 mA
3 – Axes Magnetometer + Conditioning Chain	39.5 mA
All Sensors + Conditioning Circuits + Flipping Circuits	98 mA
All Sensors + Conditioning Circuits + Flipping Circuits + 1 User Feedback LED	99 mA
All	101.7 mA

Table 7. 1

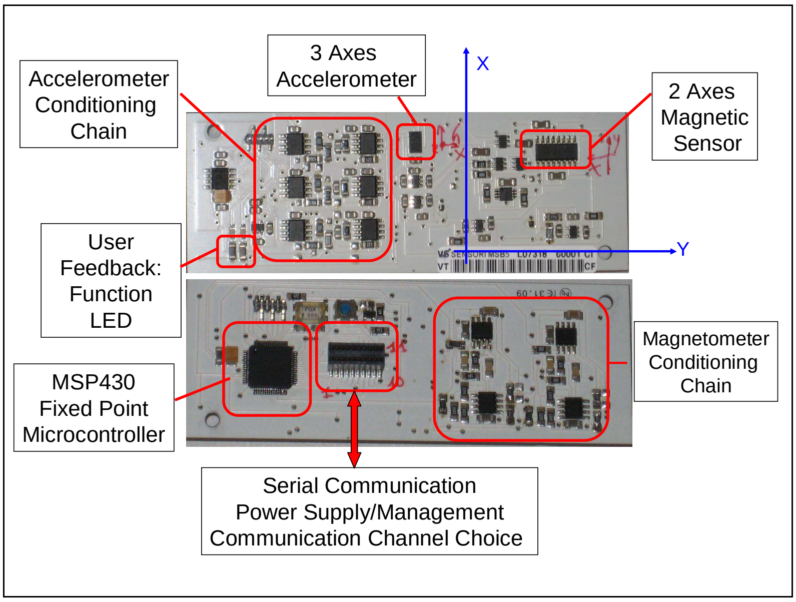


Fig. 7. 25 Multi – Sensor – Board Layout

7.3 Sensor Calibration Procedures

Traditional methods for calibrating an electronic compass are usually cumbersome and challenging for the operator who performs them (Bowditch, 2002). This methods is based on perturbation of the Eq. 7. 2 (which compute the Azimuth angle), taking into account the measurement error model. This model can be expressed as:

$$He= C_m C_{sf} C_{si}(He'+\delta He) \qquad \textbf{Eq. 7. 7}$$

where:

- He represent the actual magnetic field vector
- He' represent the measured magnetic field vector
- δHe represent the hard iron biases
- the matrix C_{si} takes into account the soft iron effects
- the matrix C_{sf} takes into account the scale factor error
- the matrix C_m takes into account the misalignment errors

Thus the Azimuth must have the following expression which is a truncated Fourier series where the coefficients are function of the hard and soft iron errors:

$$\delta(\psi)=A+B\sin(\psi)+C\cos(\psi)+D\sin(2\psi)+ E\cos(2\psi) \qquad \textbf{Eq. 7. 8}$$

The coefficients are usually calculated during a calibration procedures called “swinging”, in which the compass need to rotate near known orientation. At each orientation the Azimuth error is computed, and Fourier coefficients found. This method has several disadvantages: the Azimuth value must be known during the procedure, and this is affected by hard and soft iron errors; this calibration is valid only in an area in which the strength of the magnetic field is constant; this method is valid only if the system is utilized to compute the Azimuth and only if the magnetometer has two axes.

An alternative to the method of “swinging” is presented in (Gebre-Egziabher, 2001), in which the procedure does not require external references and it is performed also if the system is not utilized to compute Azimuth. This method is based on a non- linear estimation technique based on the fact that the Lissajous figure of two perpendicular axis not affected by errors, is a circle. Utilizing a two steps estimator based on Kalman Filter in which states are the sensor errors, magnetometer errors are estimated. This errors are utilized to calibrate the magnetometer. This method is particularly robust because only a small part of the Lissajous figure is required for the estimation.

A real time, three axes calibration method is developed in (Crassidis, 2005), utilizing an extended Kalman filter. The procedure does not require external references and it requires the determination of the magnetometer bias, scale factor and non- orthogonality corrections.

When a reference Azimuth is unavailable the simplest method of calibration is to rotate the compass on a horizontal surface and to find the maximum and minimum values of the X and Y magnetic axes. These values can be utilized to compute the magnetometer scale factor and bias (Caruso, 2007a).

A compass calibration algorithm which applies neural network non-linear mapping between the compass Azimuth and the true Azimuth based on the fact that the incorrect heading estimates due to the magnetometer biases, scale factors and declination angles have a nonlinear relationship with the true heading is shown in (Wang, 2006). When an external heading reference is available, neural networks are trained to model this nonlinear relationship. After that, the trained neural networks can be utilized to convert the compass heading into the correct heading. This algorithm can be used when magnetic disturbances and tilt compensation errors exist.

A comparison of different type of compass calibration techniques is shown in (Stirling, 2003).

As it can be seen from the above summary the compass calibration methods can be divided into two types: those that requires the reference heading and those that do not require. Furthermore, not all the methods take into account the problem of *tilt error* in the case of Azimuth computation calculating Azimuth through a two-axes magnetic sensor (as it was utilized in this PhD work). In the last case (as mentioned in Paragraph 7.1) it is necessary to estimate the Dip Angle.

Taking into account the above issues, (Cho, 2005) presents a compass calibration method for a compass based on a two-axes magnetic sensor, that can be seen as a three steps procedure (summarized in Fig. 7. 26):

- First step: horizontal rotation of 360°. This allows to find the maximum and minimum values of both axes (Hex_{max}, Hex_{min}, Hey_{max}, Hey_{min}). Through these we can calculate the bias and the scale factor value of each axes:

$$Bias_x = \frac{Hex_{\max} + Hex_{\min}}{2}; \qquad Bias_x = \frac{Hex_{\max} + Hex_{\min}}{2}$$ **Eq. 7. 9**

$$\overline{SF}_x = \frac{2}{Hex_{\max} - Hex_{\min}}; \qquad \overline{SF}_y = \frac{2}{Hey_{\max} - Hey_{\min}}$$ **Eq. 7. 10**

These allow to calculate the new value of X and Y axes measure:

$$\overline{Hex} = (Hex - Bias_x)\overline{SF}_x$$ **Eq. 7. 11**

$$\overline{Hey} = (Hey - Bias_y)\overline{SF}_y$$

- Second step: horizontal Azimuth orientation. The operator must direct to a fixed but *non-a-priori* known Azimuth and the system must calculate this.
- Third Step: random inclination at the same Azimuth of the above step. The operator must maintain the Azimuth and must tilt the compass of a random tilt angle (including Pitch and Roll).

The system must calculate the tilt error and now is able to calculate a Estimate of Dip Angle (δ_e) using this formula:

$$\delta_e = \arctan \frac{\overline{Hex}(\sin\Theta \sin\Phi - \cos\Phi \tan\alpha) - \overline{Hey}\cos\Theta}{\sin\Theta\cos\Phi\tan\alpha - \sin\Phi}$$ **Eq. 7. 12**

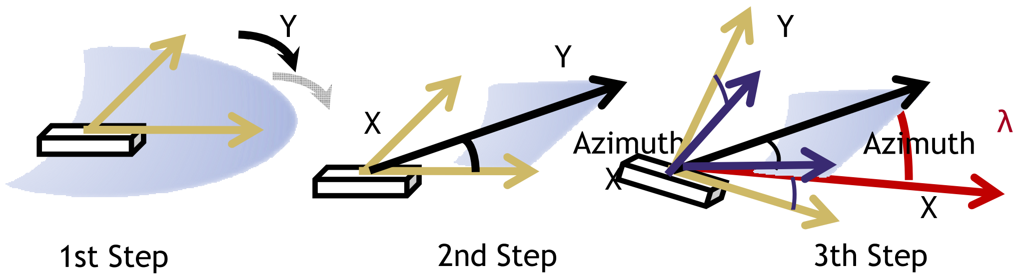


Fig. 7. 26 Typical Compass Calibration Approach

It can be seen that the procedure does not requires the benchmark heading. However, this method presents some drawbacks. First of all the Azimuth estimation in the Second step is done by a system not yet fully calibrated. This is not strictly a problem if the compass is perfectly horizontal but is a problem if the third step requires the Azimuth indication to maintain the position. The second drawback derives from the first: the transition between the Second and the Third steps is critical. In fact tilt the compass maintaining constant the Azimuth without its indication is very difficult. Third, the Dip Angle found is only an estimate and not the true value.

The satisfaction of the *Quality Criteria* for Positioning system led to the need to create a new compass calibration approach possessing these qualities:

- User assisted calibration
- Self – calibration
- No instruments required
- Easiness
- Speed
- Broad validity

This approach is based on the fact that when a magnetometer axes is parallel to the Earth's Magnetic Vector, this axes detects the absolute maximum value. The tilt angle (in this case the Pitch) corresponding to this maximum value, represents the Dip Angle. The new algorithm can be seen as a two steps procedure (summarized in Fig. 7. 27):

First step: horizontal rotation of 360°. Coincides with the First step of the above procedure

- Second step: North “swinging”. The operator must facing approximately on North and then, tilting in Pitch the system, must do a vertical and horizontal swing.

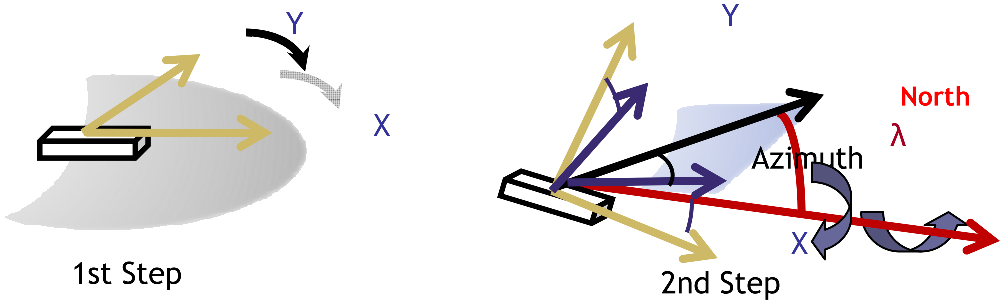


Fig. 7. 27 New Calibration Approach

It can be seen that the procedure does requires a benchmark heading but it not require an high level of precision. It can also be seen that the disadvantages in the above procedure have been solved: the critical transition has been eliminated and the facing North orientation need not to remain fixed. Moreover, the Dip Angle value is the real Dip Angle in the Earth’s surface point (coincident with the Pitch), and not the results of a complicated formula.

Another advantage of the procedure is the fact that, measuring in the first step the maximum and minimum values of the magnetic axes, these values already takes into account the presence of fixed ferromagnetic materials, *i.e.* the system is automatically compensated for the hard iron errors.

7.4 Tilt Compensation Algorithm

As mentioned in the Paragraph 7.1, the use of a two axes magnetic sensor as a compass, is valid only when the compass is positioned in a plane parallel to the Earth's surface at that point, *i.e.* perfectly horizontal. If the compass is tilted, the magnetic sensor’s components are affected by the vertical component of the field. As a result, the Azimuth computation result is different from the horizontal case. It is said that the compass is affected by a *tilt error* or non-horizontal error. Therefore, the use of a two-axes magnetic sensor in tracking applications necessitate the use of compensation to eliminate the tilt error on Azimuth angle.

In this doctoral work a trigonometric method proposed in (Cho, 2005) has been chosen. The method projected the three detected components of the magnetic field (which are those of the rotated plane of the compass) in the horizontal plane parallel to the Earth’s surface. To do this, since the sensor has only two components, the method calculates the third component, that would be the value that would occur if the sensor had three axes. The calculation of this component is expressed in Eq. 7.4 where:

- δ , is the Dip Angle derived from the calibration method

- $\overline{Hex'} = (Hex' - Bias_x)SF_x$, is the normalized X compass measure

  $\overline{Hey'} = (Hey' - Bias_y)SF_y$, is the normalized Y compass measure **Eq. 7. 13**

- $\Theta = \arcsin\frac{Ax}{g}$ is the Pitch angle $\Phi = \arcsin\frac{Ay}{g}$ is the Roll angle **Eq. 7. 14**

In Eq. 7.13 and Eq. 7.14 (normalized compass measure), Hex' and Hey' are the measure of the magnetic sensor axis. The bias values ($Bias_x$ and $Bias_y$), are calculated utilizing the Hex_{max}, Hex_{min}, Hey_{max} and Hey_{min} values derived from the calibration procedure as in Eq. 7.9. The scale factor values are different from those seen in the calibration procedure (Eq. 7. 10), taking into account the Dip Angle value. In fact, without the correction factor $\cos\delta$, when the compass is tilted, the normalized compass measure takes a value greater than 1. Using the multiplier correction factor, the maximum measurement is when the axis is parallel to the Earth's Magnetic Vector. It is only in this case that the normalized compass measure must take the value 1.

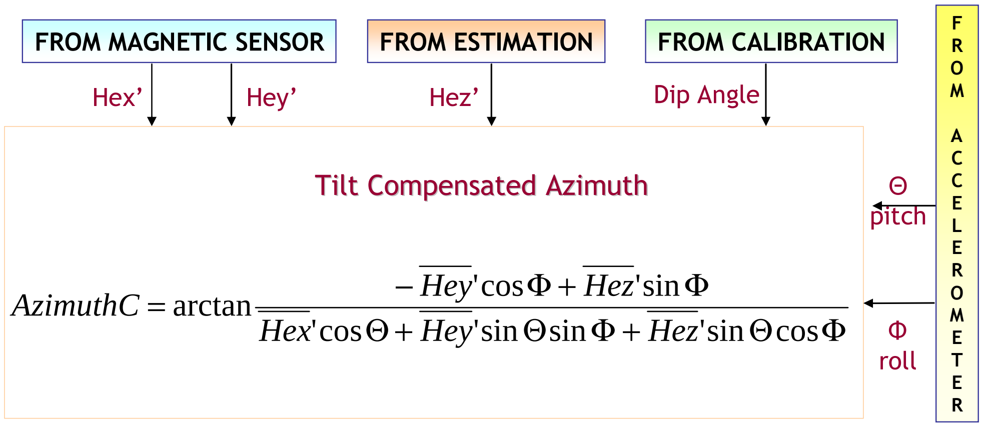
$$SF_x = \frac{2\cos\delta}{Hex_{\max} - Hex_{\min}}; \qquad SF_y = \frac{2\cos\delta}{Hey_{\max} - Hey_{\min}}$$ **Eq. 7. 15**

In (Cho, 2005) you can see how this formula was derived.

The Fig. 7. 28 shows the entire process to determine the tilt compensated Azimuth which ends with the application of the tilt compensated Azimuth formula (Eq. 7.2). As you can seen from the figure, all parameters are prepared by the previous steps:

- $\overline{Hex'}$ and $\overline{Hey'}$ derived from the magnetic sensor measure and from the calibration procedure
- $\overline{Hez'}$ derived from the calculation process using the Dip Angle derived from the calibration procedure
- Θ and Φ are the Pitch and Roll angles derived from the acceleration using the Eq. 7. 14.

The latter point is particularly critical. In fact an error on the tilt angle causes error in estimating the Azimuth. The Fig. 7. 29 shows the non-compensated Azimuth, the Azimuth compensated by pitching the compass. This is oriented on North-East. Fig. 7. 30 represents the deviation of the compensated and non –compensated Azimuth from 45° (corresponding to NE). As you can seen, the non-compensated Azimuth diverges also for small inclination. Moreover, for inclination greater that 45°, also the compensated Azimuth diverges. In this work this kind of problem are called exception (in this specific case *accelerometer exception*) of the compensation method. The handling of this exception is illustrated in the next Paragraph.



v

Fig. 7. 28 Tilt Compensated Azimuth Process

Another exception (called *0/0 exception*) to consider, is the condition in which the compass is oriented so that both axes are perpendicular to the Earth's magnetic vector. In this condition both the axes measure the minimum value. Since the Azimuth is a function of the ratio of the two components, this is conceptually equivalent to having a 0/0 form. Fig. 7. 31 shows the non-compensated Azimuth as a function of the Pitch angle, in the case of North orientation (Azimuth 0°) and Dip Angle 60°. As you can seen, when the Pitch angle is about 30 °, the Azimuth undergoes abrupt changes, inconsistent with the actual position of the compass. The handling of this exception is also illustrated in the next Paragraph.

7.4.1 Algorithm Exceptions Handling

In this Paragraph improvements to the above presented compensation method are shown. This improvements concern the *accelerometer exception* and the *0/0 exception* introduced above.

The basic algorithm for the compensation of the Azimuth angle takes into account the Pitch and the Roll angles, resulting from the Ax and Ay acceleration by the formulas Eq. 7. 14. Due to the nonperfect linearity of the accelerometer (Fig. 7. 32 shows the Ax output voltage as a function of the Pitch angle, as you can see the linearity is lost after the 50°), the measurement error increases with increasing inclination angle, starting from 45° of tilt. So it has been thought to use the third component (Az) of the accelerometer to compute one of the tilt angles instead of the other two. If, for example the Ax axis is tilted at an angle greater than 45°, the Az axis forms an angle with the horizontal plane, that is smaller than 45°. So, it has been thought to use Az axes instead of the Ax to compute the Pitch angle. To preserve the continuity of values measured, the exchange of the axes must provide hysteresis nearby the critical value (45°) using a state machine (see Fig. 7. 33). The computation of the Pitch and Roll angles is done using two of the three axis less tilted than the horizontal. For each state the computation of Pitch and Roll angles is done in this way:

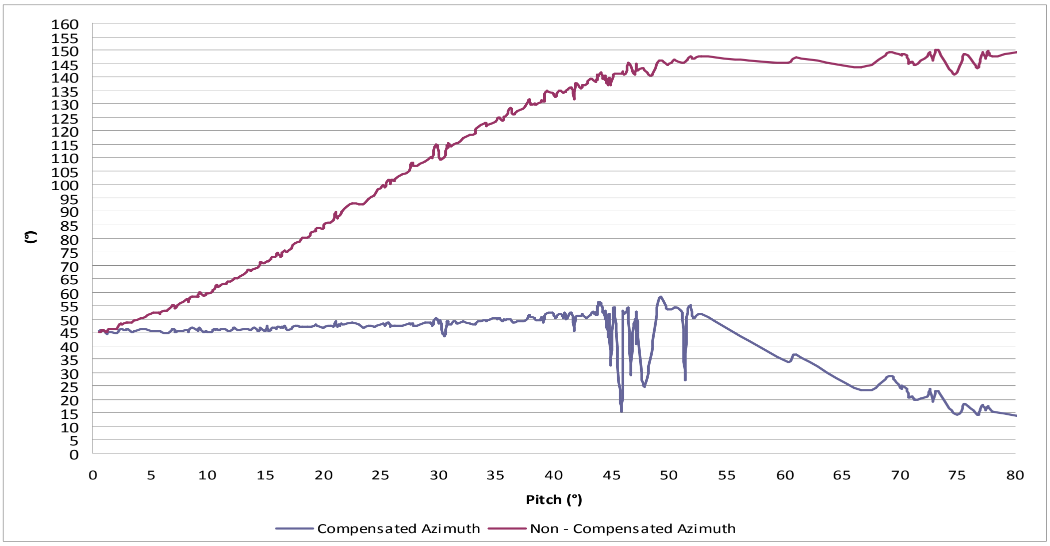


Fig. 7. 29 Non – Compensated, Compensated Azimuth tilting in pitch the compass oriented to NE

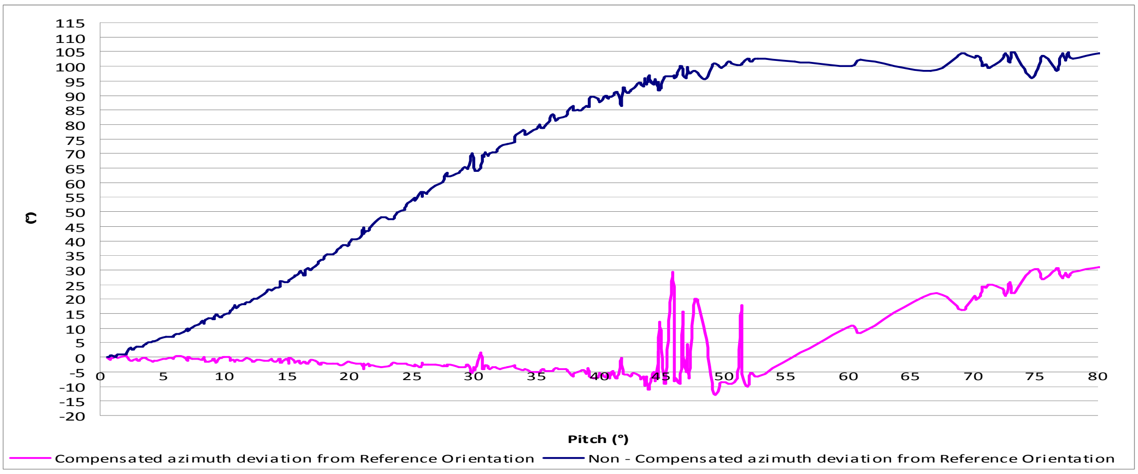


Fig. 7. 30 Non – Compensated, Compensated Azimuth deviation from reference tilting in pitch the compass oriented to NE

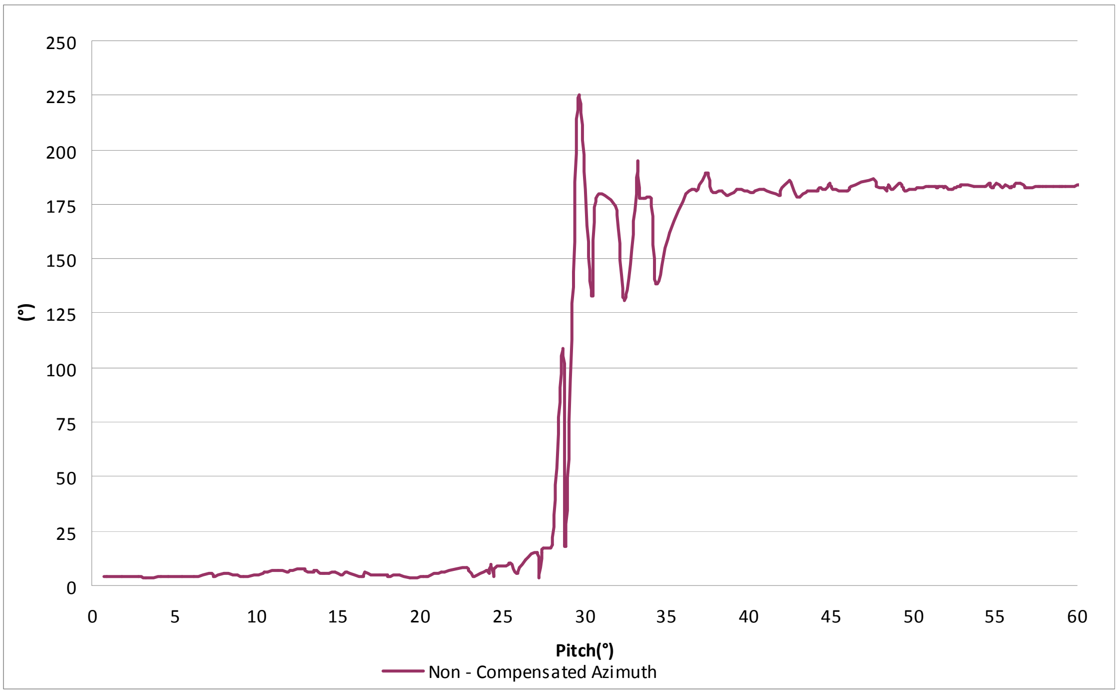


Fig. 7. 31 Non – compensated Azimuth showing the 0/0 exception

- State 0: $\Theta = \arcsin\frac{Ax}{g}$; $\Phi = \arcsin\frac{Ay}{g}$
- State 1: $\Theta = 90 + \arcsin\frac{Az}{g\cos\Phi}$; $\Phi = \arcsin\frac{Ay}{g}$
- State 2: $\Theta = -90 - \arcsin\frac{Az}{g\cos\Phi}$; $\Phi = \arcsin\frac{Ay}{g}$
- State 3: $\Theta = \arcsin\frac{Ax}{g}$; $\Phi = 90 + \arcsin\frac{Az}{g\cos\Phi}$
- State 4: $\Theta = \arcsin\frac{Ax}{g}$; $\Phi = -90 - \arcsin\frac{Az}{g\cos\Phi}$

The starting state is the State 0, since it is supposed that at the switch on, the compass is in nearly horizontal position. If not, after the first acquisition (65 ms), the State would be immediately changed.

Fig. 7. 34 shows the slope of the Pitch angle before the state machine and after the state machine as a function of the real Pitch angle, also indicating the corresponding state of the state machine. Fig. 7. 35 is a zoom of the previous from -90° to -50° of Pitch. As you can seen the computed pitch utilizing the state machine is more linear than those without.

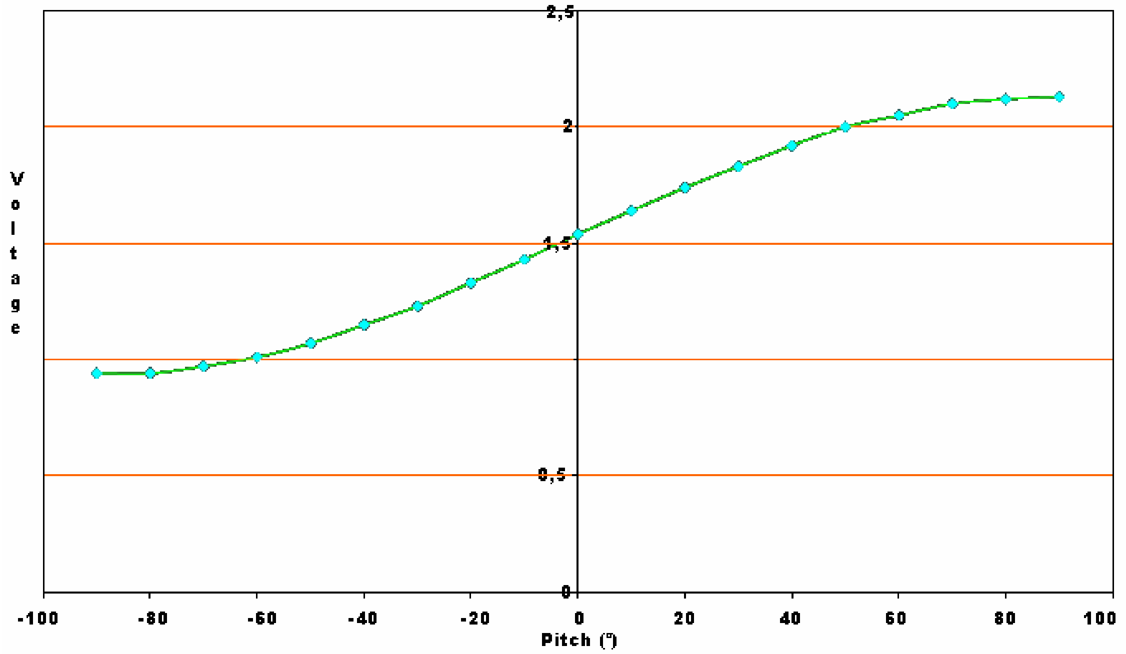


Fig. 7. 32 Accelerometer Non – linearity

Regarding the improvements on the compensated Azimuth, Fig. 7. 36 shows the compensated Azimuth tilting the compass in Pitch. It can be seen in the transition region between 40 ° and 50 °, a slight deviation from the exact value. The hysteresis, in fact, delays the exchange and causes the acceleration Ax is used after the critical value. The error is still around 2.5°.

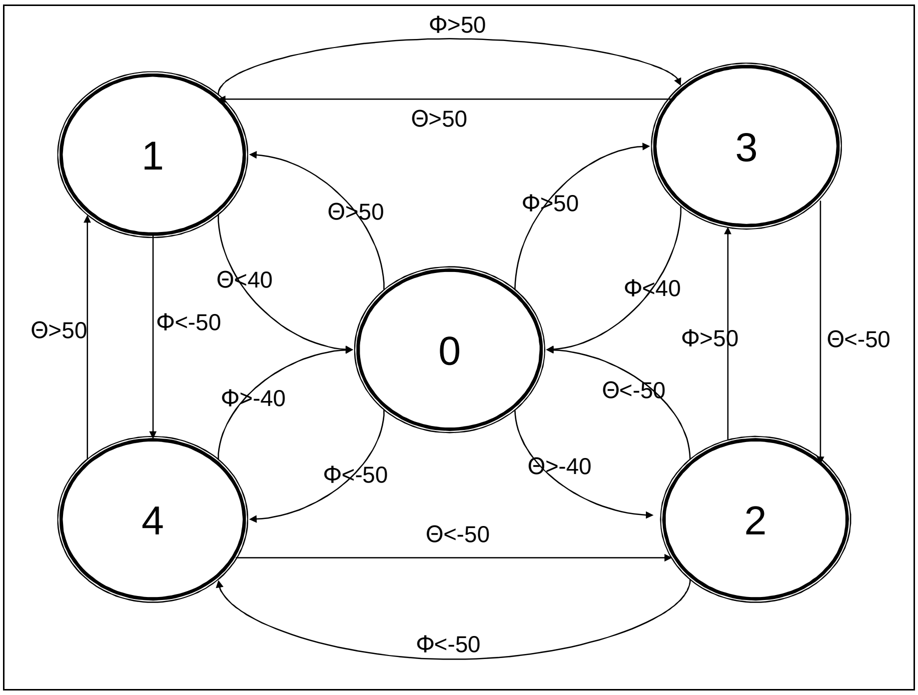


Fig. 7. 33 Changing accelerometer axes State machine

The other exception has been called in this thesis *0/0 exception*, which occurs when the compass is oriented so that both axes are perpendicular to the Earth's magnetic vector. In this condition both the axes measure the minimum value. Since the Azimuth is a function of the ratio of the two components, this is conceptually equivalent to having a 0/0 form. In general, the critical condition occur when the Pitch and Roll angles are equal to these values:

for the Pitch: $\arcsin\sqrt{\sin^2\Psi\cos^2(90-\delta)+\sin^2\Psi}$ **Eq. 7. 16**

for the Roll: $\arcsin\sqrt{\cos^2\Psi\cos^2(90-\delta)+\sin^2\Psi}$

where ψ is the Azimuth. These correspond to the values of inclination in which both axes are perpendicular to the Earth's magnetic vector.

To calculate this value would need to know the compensated azimuth at any time. This in turn depends on the values of Pitch and Roll angles. It is then understood how much difficult it is implement the control. Furthermore, the complexity of the above expressions and the scope of the compass in tracking systems (that do not require management of large inclination), led to consider in this work only some particular cases: when the compass has an axis oriented along a cardinal axis and this axis is inclined to have the angle of inclination such that is perpendicular to the Earth's magnetic vector. In this way the exception conditions are:

- X axis along the North direction and Pitch = 90 – δ
- X axis along the East direction and Roll = - 90 + δ
- X axis along the West direction and Pitch= 90 – δ
- X axis along the South direction and Roll = - 90 + δ

The algorithm developed to handle these exceptions, recognizes when one of the two axes is oriented along a cardinal axis and then, only if one of the two tilt angles assumes a value near to the critical value, do not consider the calculated non-compensated and compensated Azimuth, and imposes the correct fixed value. Fig. 7. 37 shows the handling of the exception, tilting the North oriented compass with a Dip Angle of 60°. In this case the critical Pitch is 30°.

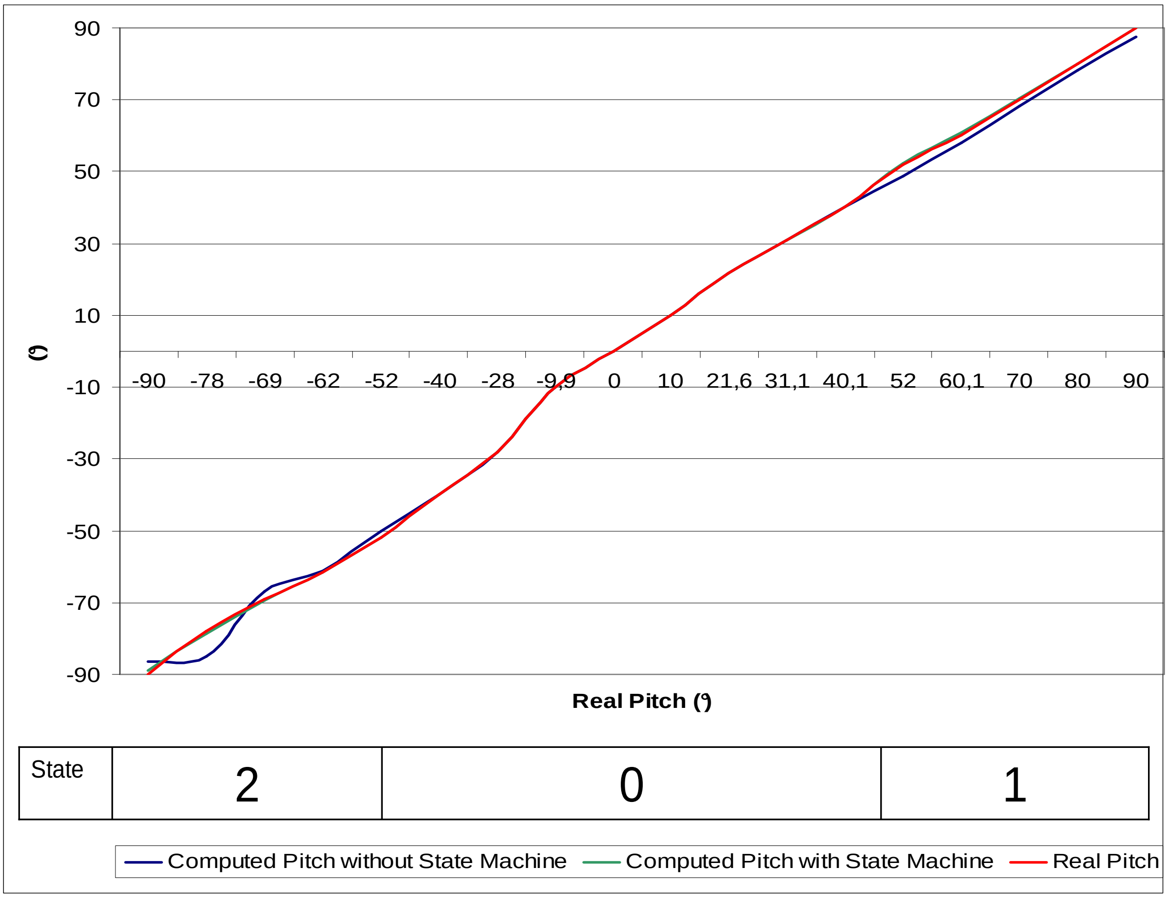


Fig. 7. 34 Pitch without State Machine vs Pitch with State Machine

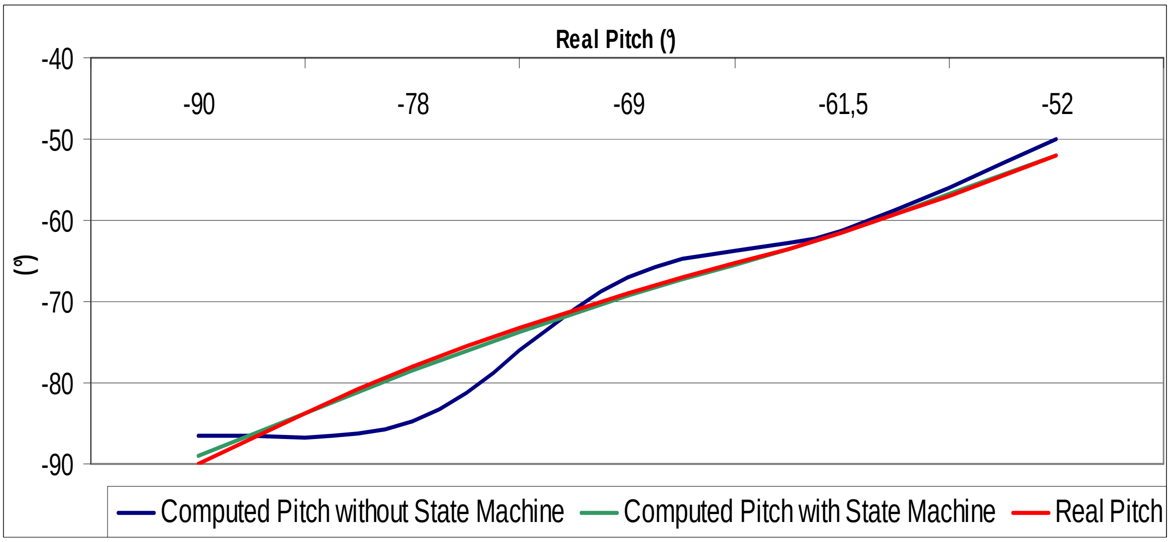


Fig. 7. 35 Particular of Pitch without State Machine vs. Pitch with State Machine

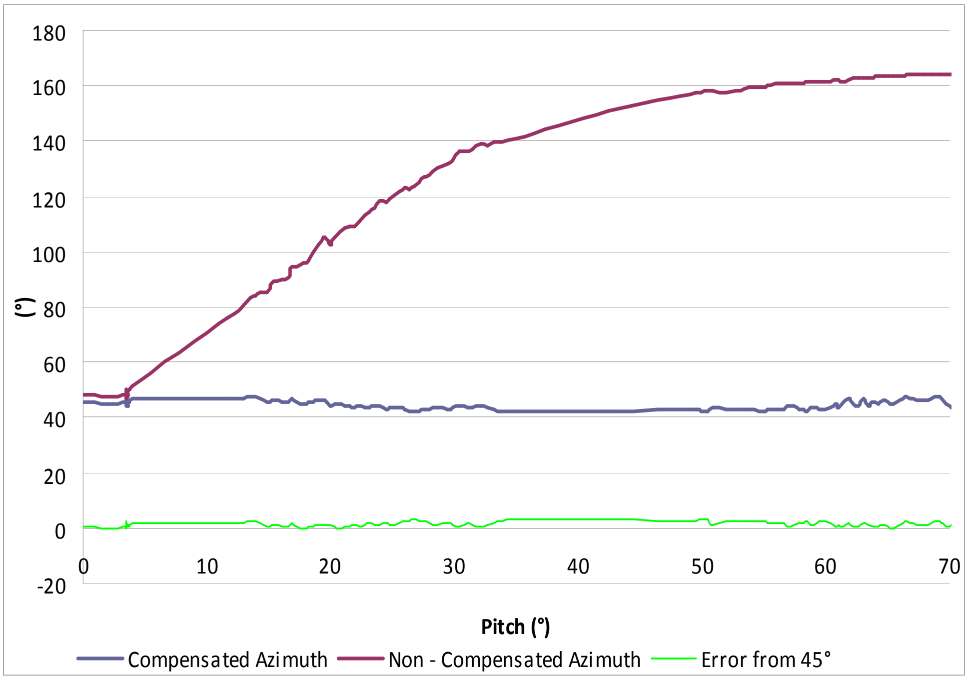


Fig. 7. 36 Non – Compensated, Compensated Azimuth and Error tilting in pitch the compass oriented to NE, after the state machine

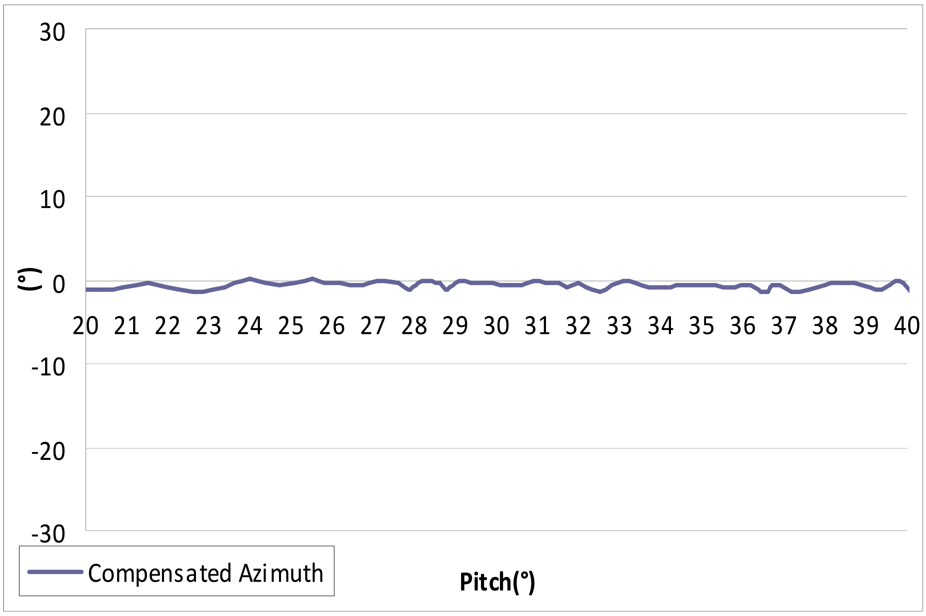


Fig. 7. 37 0/0 exceptions handling

Chapter 8

STEP DETECTION ESTIMATION

In this Chapter is presented the analysis of a human walking to detect the steps. This information can be utilized in the tracking of pedestrian user, as seen in Chapter 5. To detect the steps, the data derived from the Accelerometers have to be taken into account. Different algorithms, also depending on where sensors are worn, are performed. In this Chapter are presented two different approaches for sensors wearing on belt: the first utilizes also the frontal acceleration and the second utilizes the frontal and the vertical accelerations.

This two algorithm are compared and in Chapter 9 comparison results are exposed.

The Chapter is organized as follow: in Paragraph 8.1 the steps estimation theory is introduced and some algorithms of steps detection are proposed; Paragraph 8.2 explains the first algorithm, which utilizes also the frontal acceleration to detect steps; Paragraph 8.3 exposes the second algorithm, which utilizes the frontal and the vertical accelerations.

8.1 Steps Detection Theory and Algorithms

Each human has his own way of walking. Human physiological (height, weight, leg and arms length, physical constraints) and psychological features affected the movement. From a physics point of view, these are reflected on the motion dynamic. There are several research groups which study the dynamic of the human walking (Boulic, 1990; Kim, 2004).

By definition, walking is a form of locomotion in which the body's center of gravity moves alternately on the right side and the on left side. At all times at least one foot is in contact with the floor and during a brief phase both feet are in contact with this floor. When a person is walking, the movement can be divided into two phases: a *swing* phase and a *stance* phase. In the *swing* phase the foot is detached from the ground and it is located behind the gravity center of human body; in the *stance* phase the foot is on the ground on the heel. Each of these cycles (called Gait Cycle) identify a step.

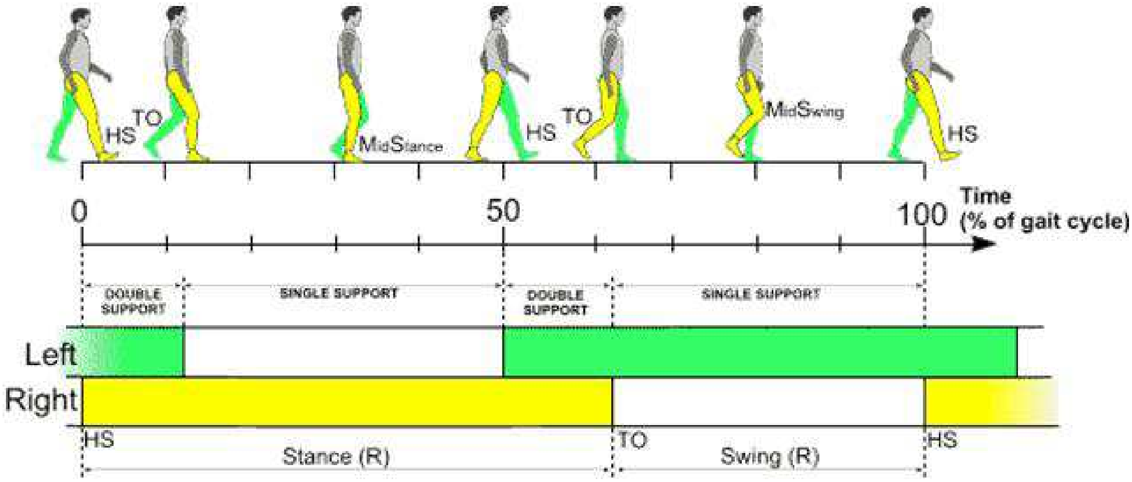
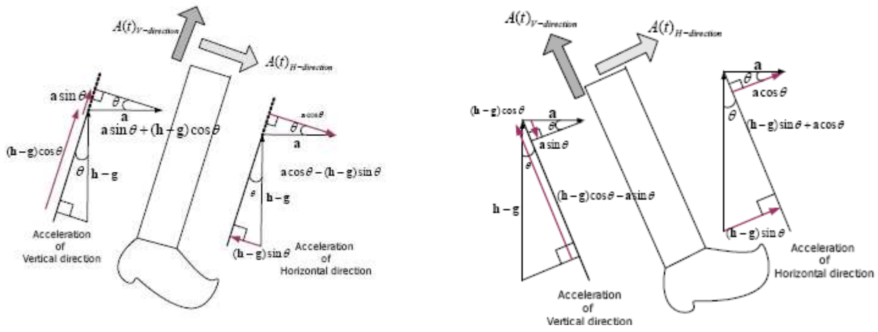


Fig. 8. 1 Gait Cycle

During a walking the Gait cycle of a foot (*e.g.* the right) is composed to (Kim, 2004):

- the right foot start the *swing* phase behind the left foot
- since the right foot is behind the left the body is raised (Fig. 8. 2_a)
- the body falls (Fig. 8. 2_b)
- when the heel touchs the ground, start the *stance* phase
- each feet touch the ground
- the left foot start its *swing* phase and the body is raised. It starts the following step.

In Fig. 8. 2 are reported the horizontal and vertical acceleration vector. As seen in (Kim, 2004) the simulated signal pattern of the frontal and vertical acceleration of a walking cycle are reported in Fig. 8. 3.



(a) **(b)**

Fig. 8. 2 Swing Phase

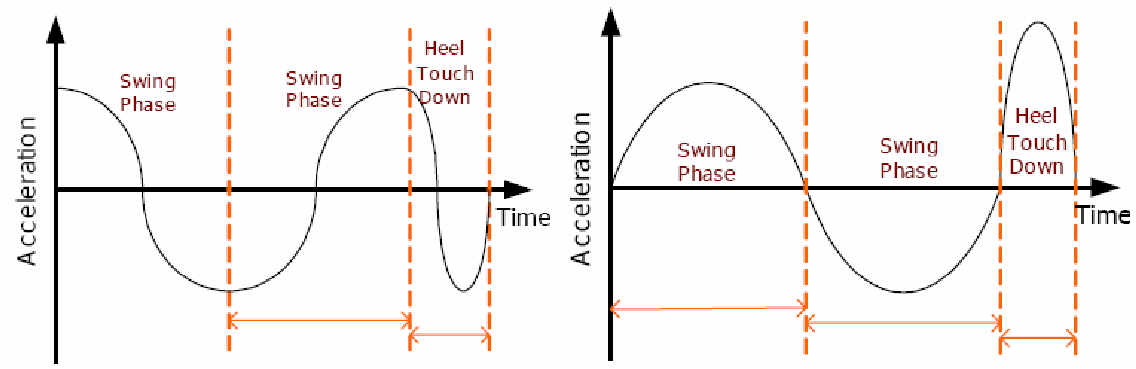


Fig. 8. 3 Vertical and Horizontal Acceleration Pattern

These patterns are described to the following equations (Jang, 2007):

$$A(t)_H = (f_Z - g)\sin\theta(t) + f_X \cos\theta(t)$$
$$A(t)_V = (f_Z - g)\cos\theta(t) - f_X \sin\theta(t)$$

Eq. 8. 1

where:

- $\theta(t)$ is the angle formed between the foot and the ground
- f_Z and f_X are the vertical and horizontal acceleration with respect to the frontal movement
- g is the gravitational acceleration

It is reasonable to utilize the Accelerations to detects steps.

Several methods are proposed to detect steps, depending also on where Accelerometers are worn, and how many acceleration are considered.

One of such method is to detect the peaks of vertical acceleration (Jirawimut, 2003a). This method depends on thresholds and is sensible to the type of walking and to the ground surface. For this reason the frontal and horizontal accelerations can be utilized. (Levi, 1996; Ladetto, 2002a) propose a method based on the upper and lower threshold on both vertical and horizontal accelerations for a belt worn accelerometer. (Kim, 2004; Beauregard, 2006) proposes a the same for an ankle worn accelerometer.

Another method is to detect the zero crossing method (Fig. 8. 4), which detect when the acceleration pattern has value zero. This method is resilient to the user's walking velocity. In (Shin, 2007; Xiaoping, 2007) this approach is proposed, utilizing the vertical acceleration for a belt worn accelerometer.

The last method to detect steps is the flat zone detection (Fig. 8. 5). In (Cho, 2002; Cho, 2003) this method is proposed, for an accelerometer worn on belt.

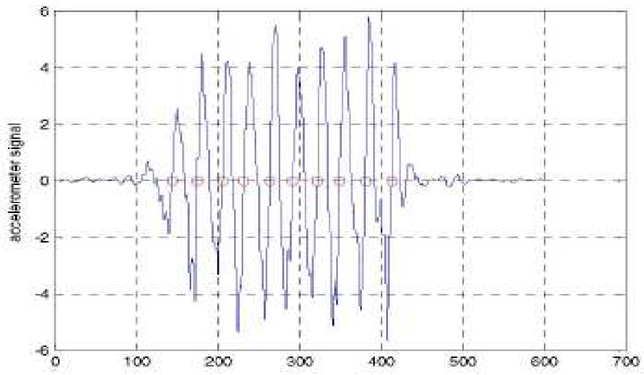


Fig. 8. 4 Zero Crossing Detection

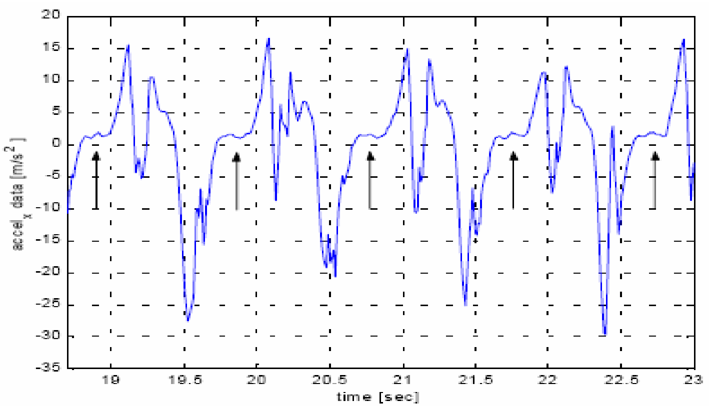


Fig. 8. 5 Flat Zone Detection

The two proposed approach are based on the peak detection method, the latter utilizing only the frontal acceleration, and the former utilizing the frontal and the vertical.

Regarding the peak detection method, the study of the pattern of the acceleration is important to detect the threshold applied to the method. Taking into account the accelerometer raw data, the vertical and frontal acceleration highlighted only the phase when the heel is on the ground. The *swing* phase accelerations is not certainly detected. Therefore, it is necessary to elaborate the accelerometer data detected. In Fig. 8. 6 is reported the pattern of the filtered frontal and vertical acceleration during a normal walking (Pettinari, 2007). The accelerometer is worn on the belt of the user. Each acceleration has the same pattern: positive peak followed by negative peak. The two acceleration sequence is:

- a positive frontal acceleration peak

- a positive vertical acceleration peak
- a negative frontal acceleration peak
- a negative vertical acceleration peak.

The acceleration pattern depends on several factors:

- user's physical characteristic
- walking velocity
- type of walking
- type of path
- where the sensor is worn.

For this reason algorithm which depends on sequence of peak are often utilized in the steps detection, instead of algorithm which depends on numerical characteristics.

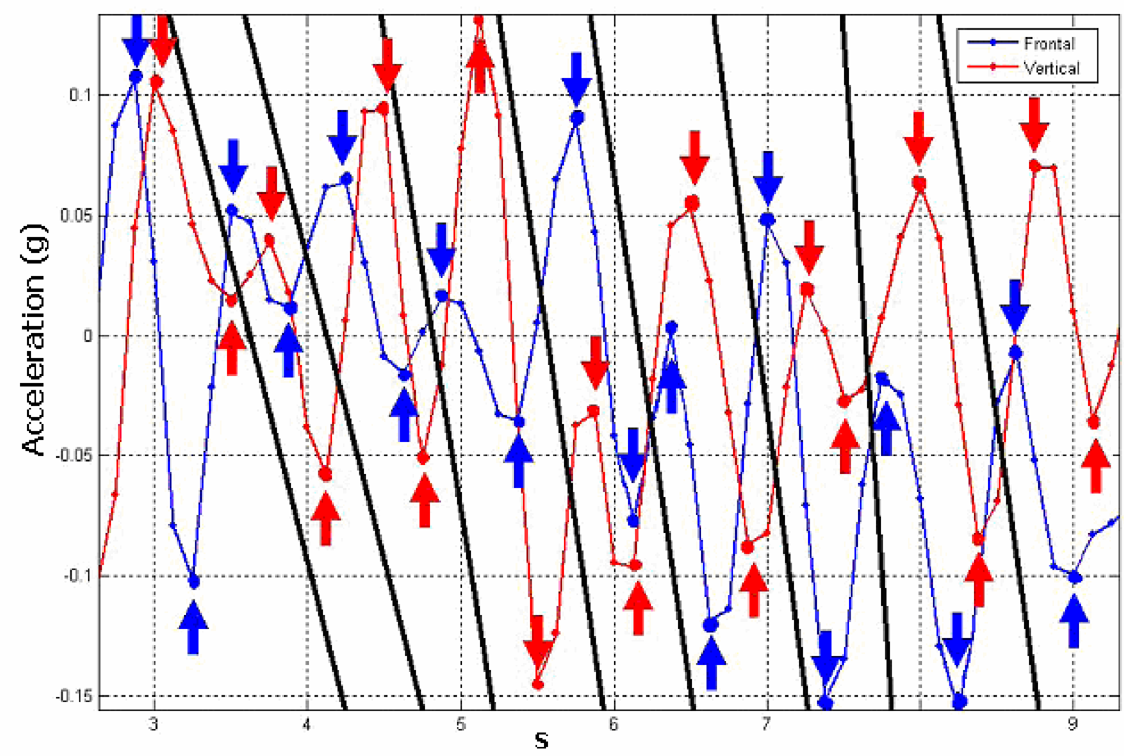


Fig. 8. 6 Walking Frontal and vertical Acceleration pattern

To eliminate the accelerometer offset due to the inclination, and to accentuate the peak, the derivative accelerations can be used, instead of the filtered acceleration (Fig. 8. 7). In Fig. 8. 8 a fewer number of steps are shown to highlight the peak sequence. In the figure the steps are highlighted with a yellow line.

In the following Paragraphs two algorithms to detect steps are shown.

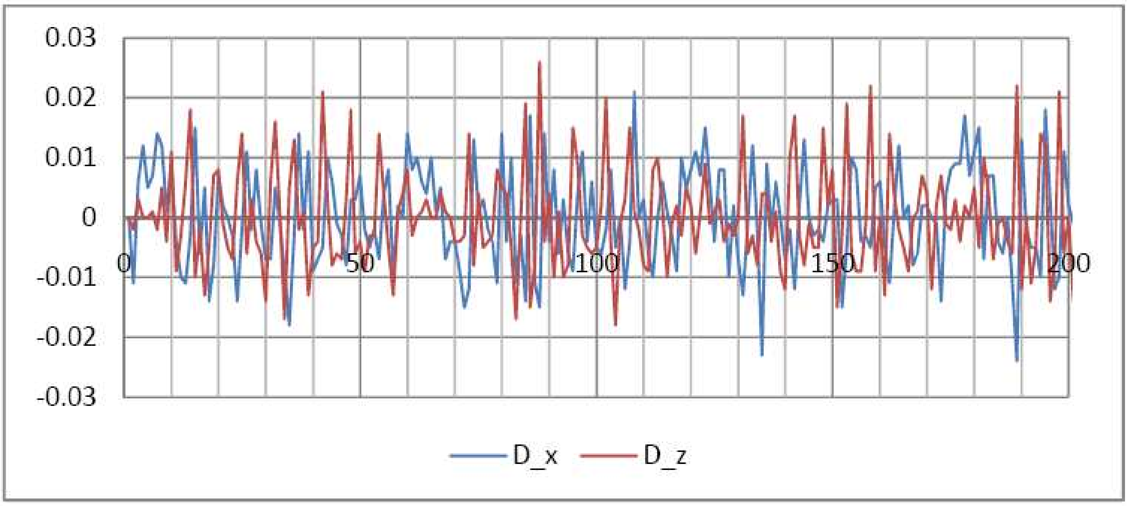


Fig. 8. 7 Walking Derivative Frontal and vertical Acceleration pattern

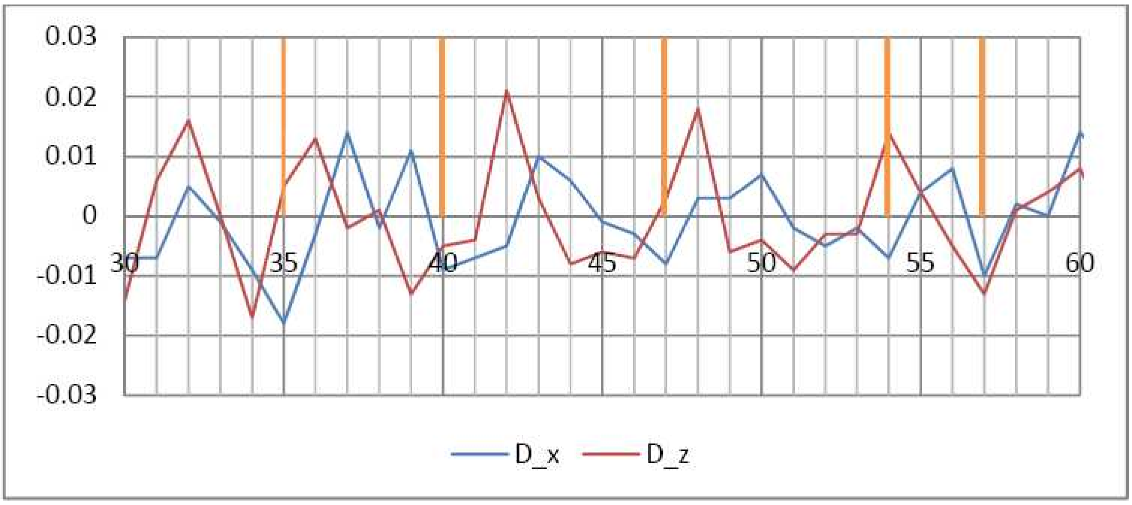


Fig. 8. 8 Walking Derivative Frontal and vertical Acceleration pattern: zoom

Particularly important in the step sequence is the choice of the filtering frequency. Analyzing the accelerometer patterns for a normal walking, using a belt wears sensors, the frequency range is between 0 and 3 Hz. The power spectral density of the three accelerations is shows in Fig. 8. 9. The power spectral density of the frontal and vertical accelerations has significant values for frequencies lower than 1.5 Hz. In particular the frontal and vertical accelerations has two frequency peak at 0.5 Hz and 1 Hz. The vertical acceleration presents the 0.5 Hz ones lower than the frontal one. The lateral acceleration presents non null power spectral density up to 3 Hz. In the steps detection, only the vertical and frontal accelerations are considered. For this reason the cut-off frequency of a filter can be fixed at 2.5 Hz. This frequency permits to delete the spurious accelerations components, without introducing a large delay.

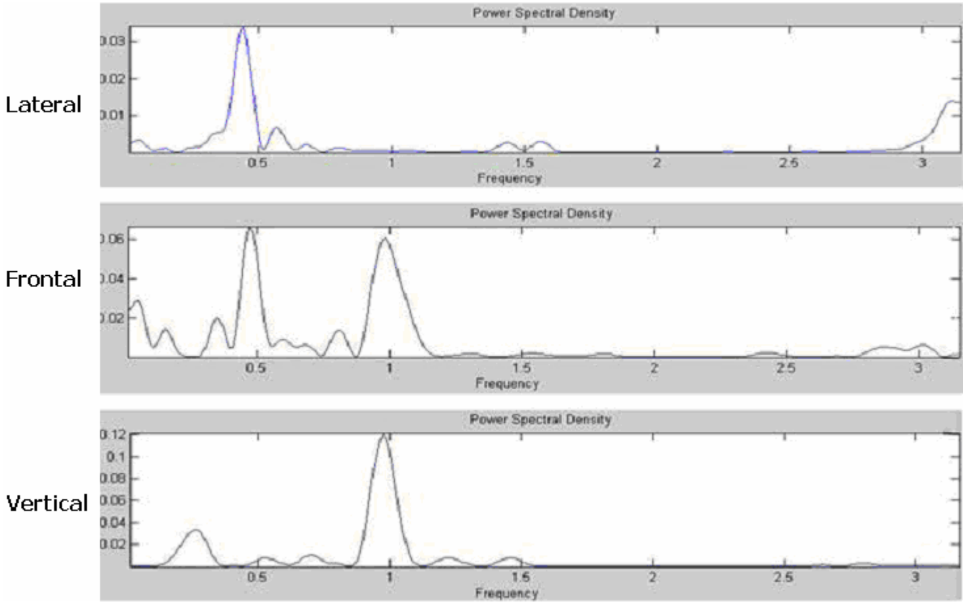


Fig. 8. 9 Three acceleration Power spectral density

Utilizing three accelerations instead of only one or two, permits to recognize different movements, such as lateral movements, rotation, go downstairs and upstairs:

- lateral movements: In Fig. 8. 10 are shown the lateral and vertical acceleration for this movement. The lateral acceleration has more marked and regular pattern. A lateral step pattern is composed of four peak: the first and the third are negative, the second and the fourth are positive. The lateral steps detection can be performed utilizing only the lateral acceleration.
- Rotation: In Fig. 8. 11 are shown the lateral and vertical accelerations for a sequence of two 90° counter-clockwise and clockwise rotations. As it can be see, the lateral acceleration gives the better indication. This component present three peaks for the first 90° counter-clockwise rotation: two positive and one negative. The component presents four peaks for the first 90° clockwise rotation: two positive and two negative. The other two rotations presents always four peaks. Theoretically the 90° rotation has to present three peaks. The first one is due to the changing of the direction of rotation. The number of peaks is influenced to the number of steps and to the angular velocity. This is because, some peaks can be missed due to a sudden rotation. The rotation detection can be performed utilizing only the lateral acceleration.
- Downstairs and upstairs: In Fig. 8. 12 are shown the lateral and vertical accelerations for the upstairs (Figure above) and downstairs (Figure below) for a 15 stairs in sequence. As it can be see from the figure, the most purposeful acceleration is the vertical. Besides, the pattern is different for the two movements: the downstairs movement has a bigger vertical component. For this reason, the recognition of the two movements has to be different.

In the downstairs movement, the vertical acceleration has summed the gravitational acceleration. The acceleration variation are for this reason more marked. In the upstairs movement the gravitational acceleration is subtracted. The acceleration variation are less marked. For these reason the detection of upstairs movements is difficult.

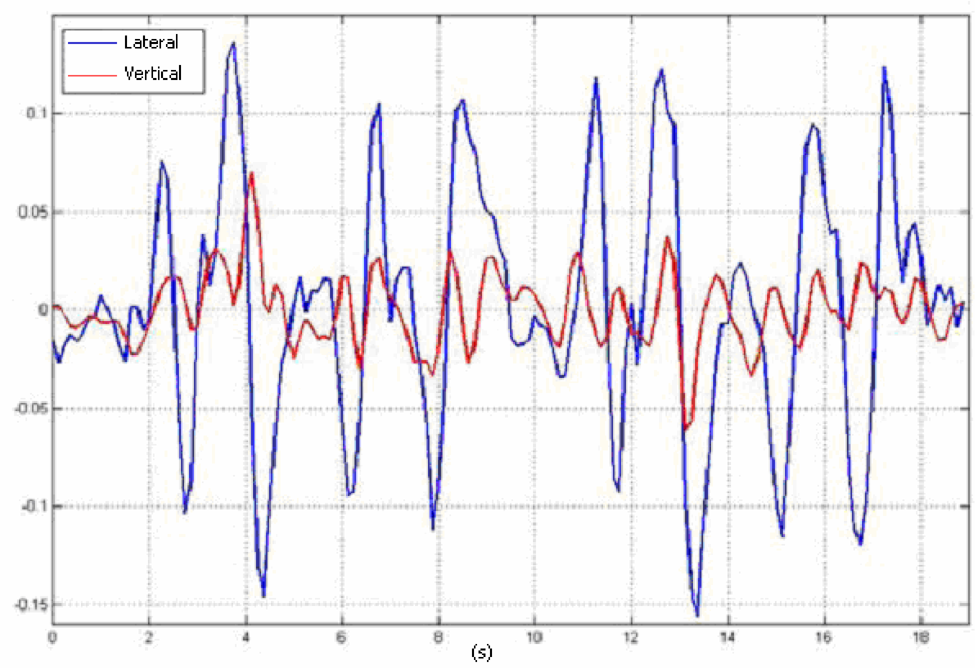


Fig. 8. 10 Lateral Movements: Vertical and lateral Accelerations

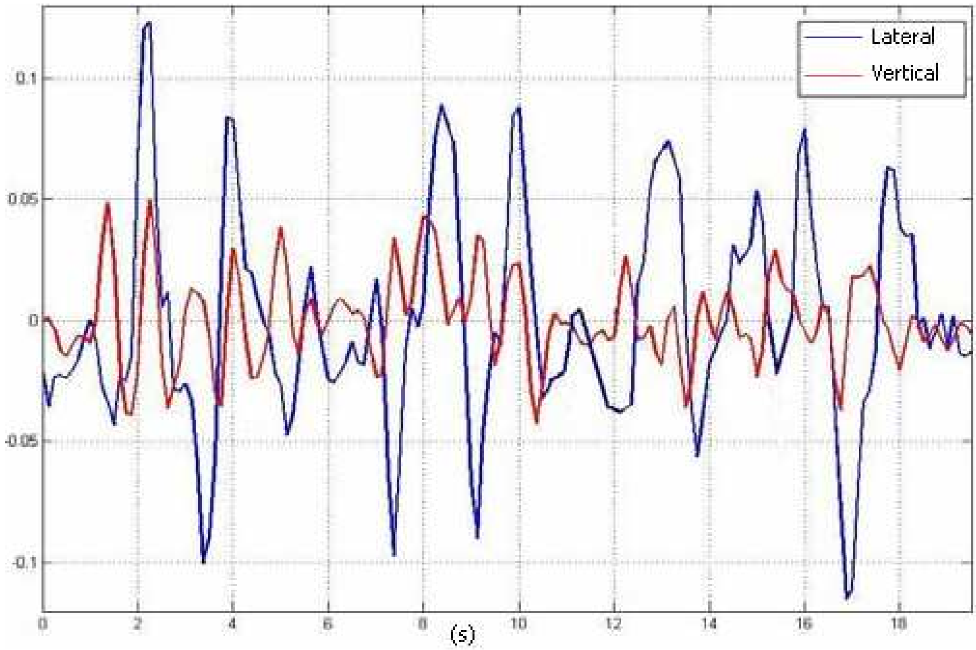


Fig. 8. 11 Rotation: Vertical and lateral Accelerations

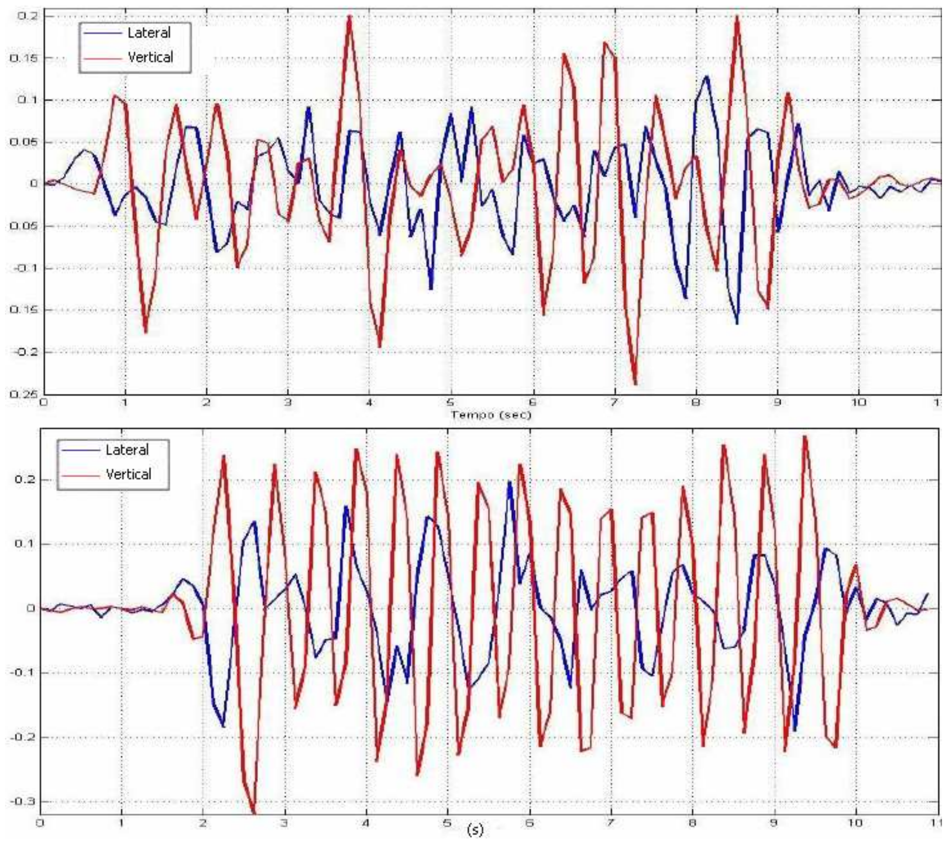


Fig. 8. 12 Downstairs and upstairs: Vertical and lateral Accelerations

Therefore, it is necessary to utilize also the frontal acceleration in the recognition (Fig. 8. 13). This component presents a sequence of positive and negative peaks. The problem is that this peaks are not much marked.

The downstairs and upstairs movements necessitate of a sophisticated algorithm which takes into account the vertical and frontal acceleration.

8.2 Steps Detection using the Frontal Acceleration

The first steps detection algorithm considered is based on the frontal acceleration only.

As seen in the Paragraph 8.1, the acquisition frequency and the filtering are relevant constraints for the step detection algorithms. Taking into account this constraints, the steps detection algorithm has to be able to detect the two succeed frontal accelerometer peak (Fig. 8. 14):

- positive acceleration peak (Fig. 8. 14 green arrow)
- negative acceleration peak (Fig. 8. 14 red arrow)

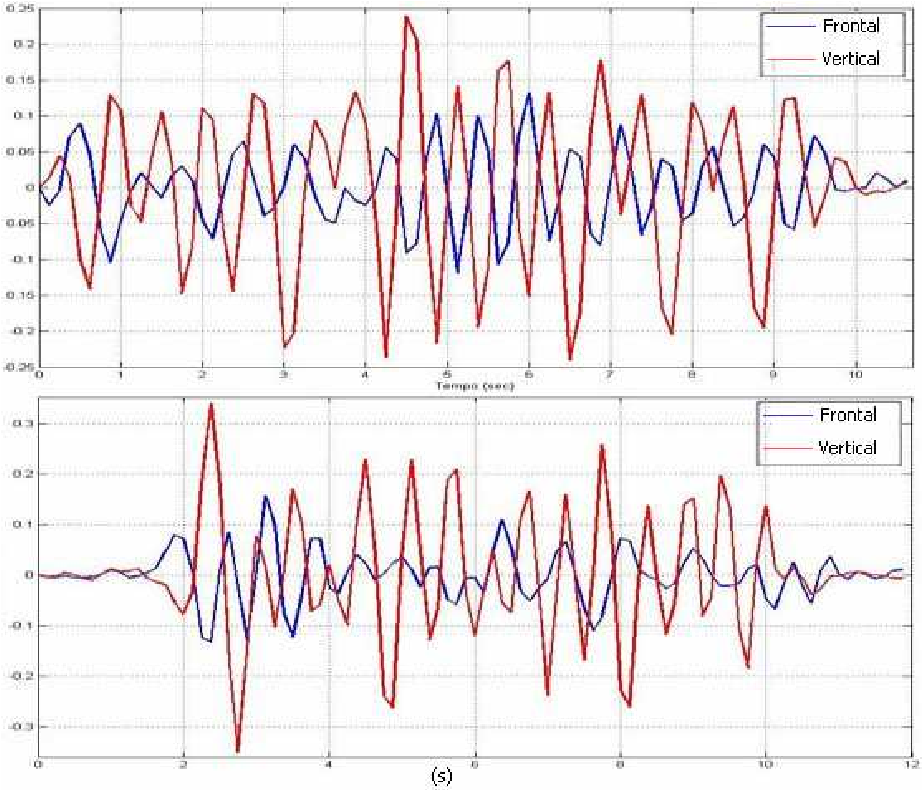


Fig. 8. 13 Downstairs and upstairs: Frontal and vertical Accelerations

A simple method to detect steps starting from the acceleration pattern, is a Finite State Machine (Pettinari, 2007) based on the derivative of the frontal acceleration (Fig. 8. 15). The state transitions are performed observing some thresholds on the derivative accelerations.

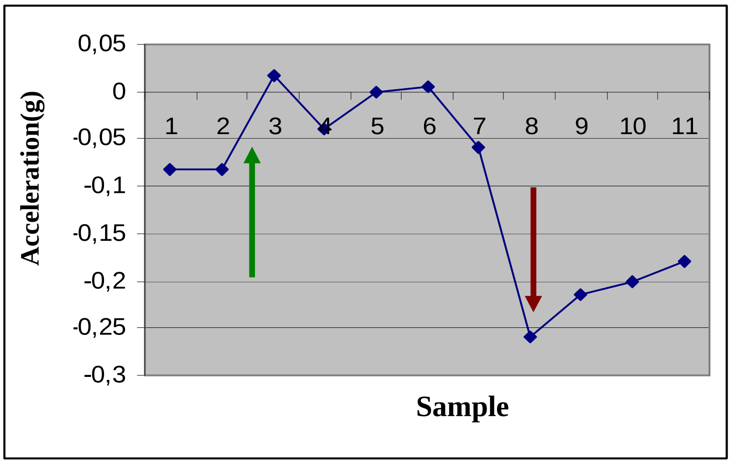


Fig. 8. 14 Frontal Acceleration Peak

The state machine states are:

- *NoWalk*: it is the idle state. The state machine is waiting for a peak event and the user is still.

- *Positive*: the derivative acceleration goes above the positive threshold (*aTh1*) which represents the fact that the derivative acceleration is positive. This event could be the beginning of a step.
- *Negative*: the derivative acceleration goes under the positive threshold (*aTh1*) but it is negative. The state machine goes in this state if the transition event start the *Positive* state.
- *Peak*: the derivative acceleration goes under the first negative threshold (*aTh2*). This event could determine a step.
- *StayPeak*: if there is another negative derivative acceleration after the one which causes the *Peak* transition. The step is not yet determined.
- *Wait*: if there is a new positive acceleration peak, the state machine waits for a new step. In this state a new step is counted.

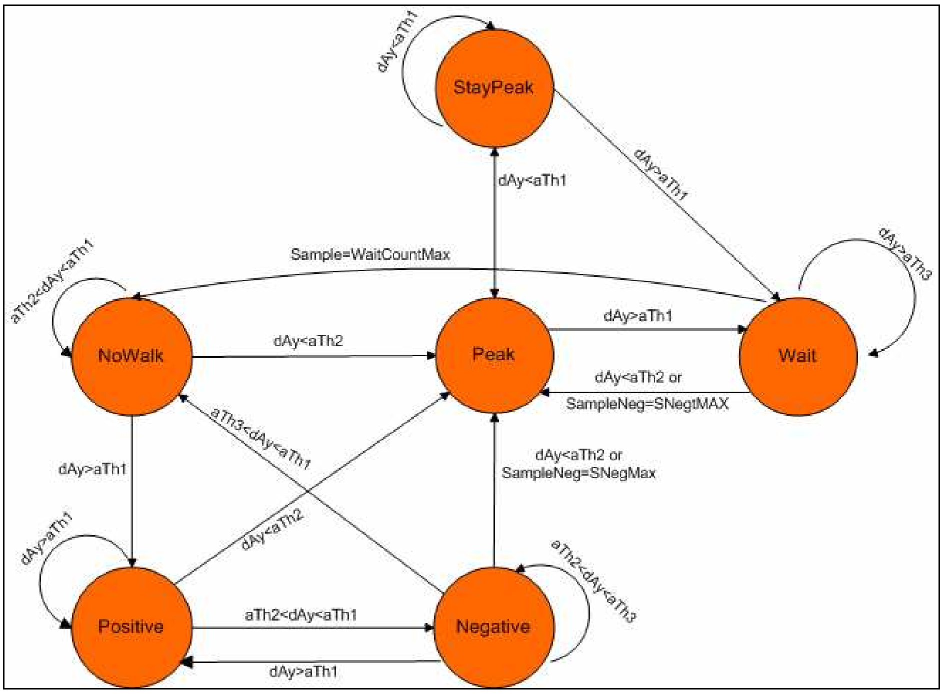


Fig. 8. 15 Frontal Acceleration State Machine Steps Detection

The transition events are not only the derivative acceleration, but also temporized events:

- *aTh1* is the positive threshold. If the derivative acceleration is above this value, it could be the beginning of a step.
- *aTh2* is the first negative threshold. If the derivative acceleration is under this value, it could be the detection a step.
- *aTh3*: is the second negative threshold. It is necessary when the negative derivative acceleration do not go under *aTh2*. The value is checked if the positive peak is occurred.
- *WaitCountMax*: is the maximum value of the number of samples (*Sample*) after that the user is considered to have stopped.

- *SNegMAX*: is the maximum value of the number of negative samples (*SampleNeg*) after which a negative peak is considered also if the derivative acceleration do not go under *aTh2*. It is used in the *Wait* and *Negative* state when a positive peak of derivative acceleration has been already detected.

The state machine functioning is shows in Fig. 8. 16. The figure represents the derivative frontal acceleration in the figure above, and the states in the figure below. As it can be see the state machine, after the first step detection, remains between the *Peak* and the *StayPeak* state. The state machine return in the *NoWalk* state when the user ends the walking. In the figure above, the reckoning of a new step is indicated with a red point. This event occurs in the *StayPeak* state or when the state goes out the *Peak* state.

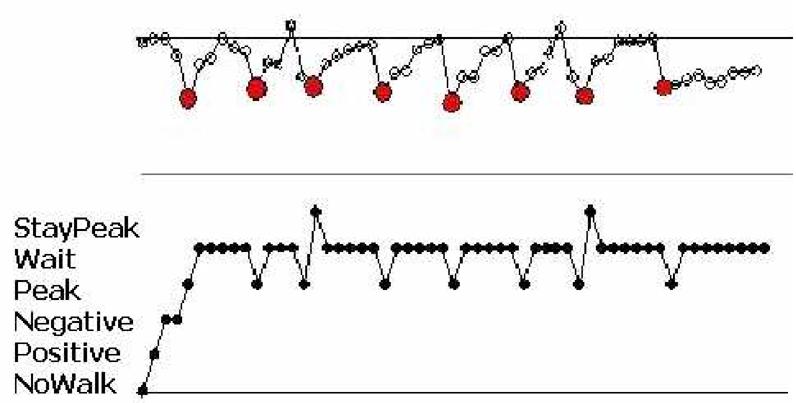


Fig. 8. 16 Steps Detection State Machine

Utilizing the state machine which detects the user's steps, it is also possible to recognize a simple user activity: if the user is walking or not. If the state of the state machine remains on *StayPeak*, *Wait* or *Peak* values, the user is W*alking*. When the state is *NoWalk*, *Positive* or *Negative*, the user is *Not Walking*. As it can be see in Fig. 8. 17, where the derivative acceleration and the walking activity is reported, the walking indication is updated with an acceptable delay.

Regarding the algorithm performance, a series of practical tests are performed with different users and different types of walk:

- 10-15 steps straight walking: 85-90% of step detection for normal and slow walking
- 10 step 1 step and stop walking: this walking is characterized by one step and the user stops. The steps reckoning is around 100% for different walking
- mixed walking: walking which includes straight lines, stop, rotation. The steps reckoning is around the 75%.

In Chapter 9 more results will be shown.

It is important to notice that the state machine depends on two thresholds which have to be calibrated for each user. Alternatively, statistical analysis on a large sample can be performed to determine these thresholds.

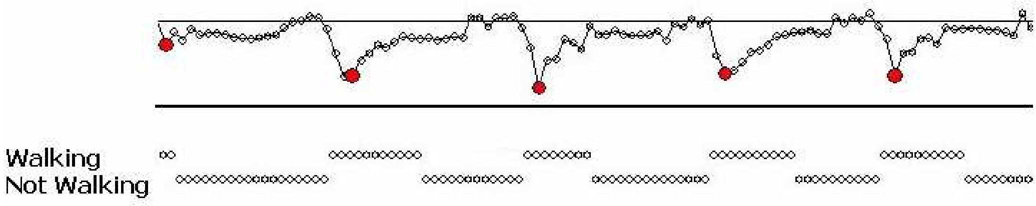


Fig. 8. 17 Walking activity

8.3 Steps Detection using the Frontal and Vertical Accelerations

The second steps detection algorithm considered is based on the frontal and the vertical acceleration. The combination of the two acceleration is necessary to make the steps detection independent to the angle between the foot and the ground. In fact this depends on the type of ground surface and on the type of walking.

As seen in the Paragraph 8.1, the acquisition frequency and the filtering are relevant constraints for the step detection algorithms. Taking into account the two accelerations, the algorithm proposed introduce a cut-off frequency of 16 Hz. This allows to highlight the pattern of the walking acceleration, deleting the peaks due to the up and down motion of the accelerometer.

Also in this case, the steps detection algorithm is a state machine which keeps track of the peaks. The state machine proposed detects a sequence of two positive peaks and two negative peaks and recognizes the sequence as a step. Information of which peak is the first (vertical or horizontal) is irrelevant.

Also in this case thresholds values on the derivative accelerations are necessary to detects peaks:

- *Thl*: low level threshold (Fig. 8. 18)
- *Thh*: high level threshold (Fig. 8. 19).

The former threshold is introduced because sometimes during a step detections, not all the four peaks occurs. In Fig. 8. 19 is shown the last steps of a walking. The red and blue points show the steps peaks. The next oscillations represents the stop. In this situation, the last steps presents a negative vertical peak less than *Thl*. In this case, the peak detection do not occur. Solving the problem by reducing the *Thl* threshold, could lead to detects spurious peaks. Therefore, a second threshold (*Thh*) is introduced. When the derivative acceleration is above this threshold in the case of missing peak, the two peaks are counted. So, this mechanism confirms an high peak in absence of the previous only if the high peak occurs after a temporal period.

As in the previous case, the state machine depends on two user dependent thresholds, which have to be calibrated.

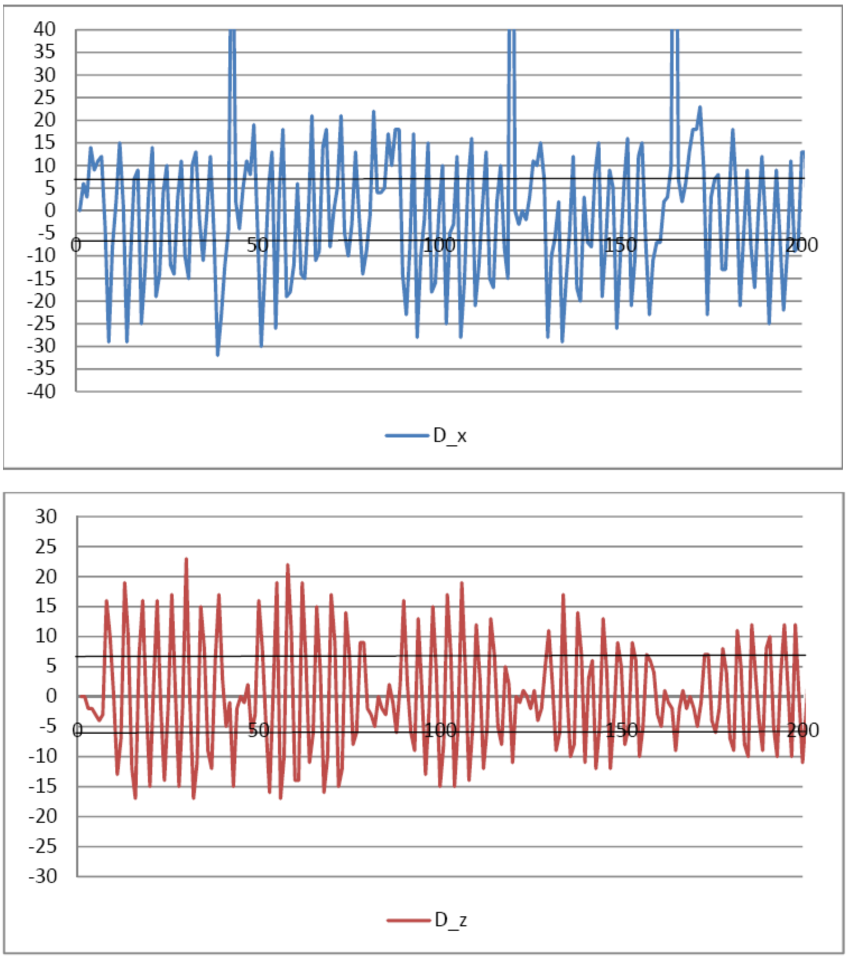


Fig. 8. 18 Frontal and Vertical Acceleration Low level threshold

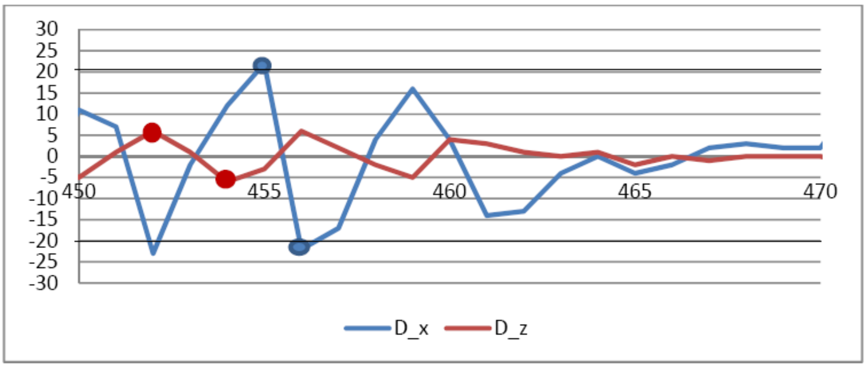


Fig. 8. 19 Frontal and Vertical Acceleration High level threshold

The state machine is reported in Fig. 8. 20. The state machine states are:

- *IDLE*: the state machine is waiting for an event that could represents the start of a step
- *+X*: the derivative frontal acceleration goes above *Thl*. In this state the state machine is waiting for other peaks. If the state machine remains on this state more than a set time interval, the state

returns in *IDLE*. If each vertical and frontal accelerations go under -*Thh*, a new steps is counted and the state return on *IDLE*.

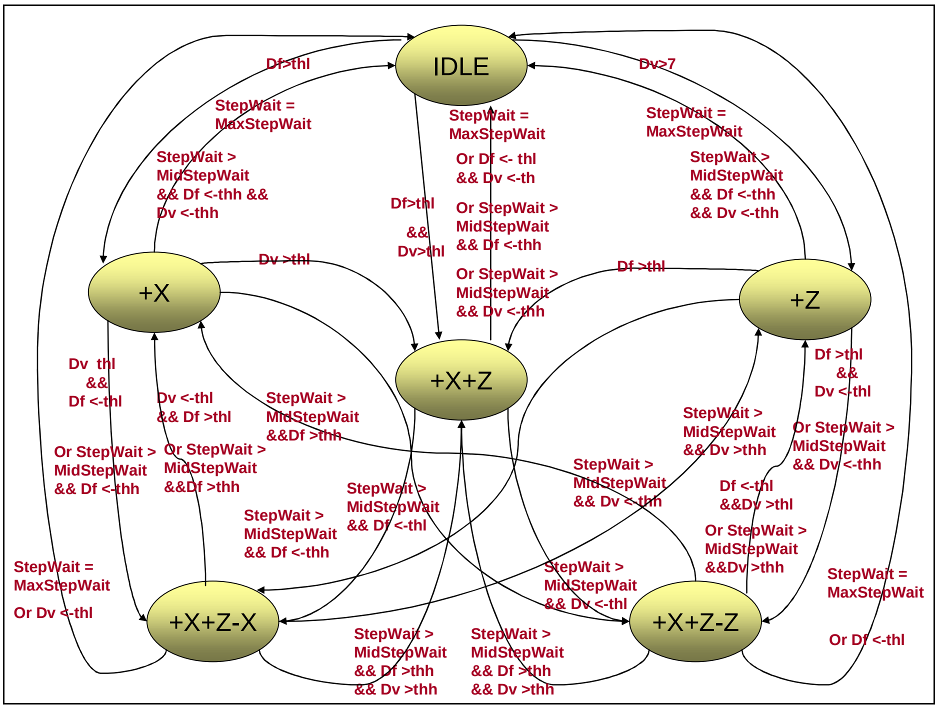


Fig. 8. 20 Frontal and Vertical Acceleration State Machine Steps Detection

- *+Z*: the derivative vertical acceleration goes above *Thl*. In this state the state machine is waiting for other peaks. If the state machine remains on this state more than a set time interval, the state returns in *IDLE*. If each vertical and frontal accelerations go under -*Thh*, a new steps is counted and the state return on *IDLE*.
- *+X+Z*: the derivative vertical acceleration goes above *Thl*, after the derivative frontal acceleration. In this state the state machine is waiting for the negative peaks. If the state machine remains on this state more than a set time interval, the state returns in *IDLE*. If both vertical and frontal accelerations go under -*Thl*, a new steps is counted and the state return on *IDLE*. If one of the two accelerations go under - *Thh*, a new steps is counted and the state return on *IDLE*.
- *+X+Z-X*: the derivative frontal acceleration goes under -*Thl*, after the positive peaks. In this state the state machine is waiting for the vertical acceleration peak. If the state machine remains on this state more than a set time interval, the state returns in *IDLE*. If vertical acceleration goes under -*Thl*, a new steps is counted and the state return on *IDLE*. If also one or both accelerations go above *Thl*, a new step could be start.
- *+X+Z-Z*: the derivative vertical acceleration goes under -*Thl*, after the positive peaks. In this state the state machine is waiting for the frontal acceleration peak. If the state machine remains

on this state more than a set time interval, the state returns in *IDLE*. If frontal acceleration go under -*Thl*, a new steps is counted and the state return on *IDLE*. If also one or both accelerations go above *Thl*, a new step could be start.

Regarding the algorithm performance, a series of practical tests are performed with different users and different types of walk. In Chapter 9 more results will be shown.

Chapter 9

RESULTS

In this Chapter results are shown, taking into consideration the comparison between the exposed techniques concerning the direction estimation, the step detection, the step length estimation and the positioning of the user. In the Chapter the results are divided in the following manner:

- in the first Paragraph of each section the results concerning the mature and well tested approaches are reported;
- in the second Paragraph of each section the results concerning the new approaches developed in this thesis are exposed. This is a recent development that must be further tested;
- in the third Paragraph of each section the comparison between the above approaches is shown and annotated.

Paragraph 9.1 shows the results on the estimation of the user's direction; Paragraph 9.2shows the results on the detection of steps occurrences, considering also female user; Paragraph 9.3 shows the results on the estimation of the step length; Paragraph 9.4 shows the results on the user positioning in the two different approaches.

9.1 Direction Estimation Comparison

As seen in Chapter 5, the direction of the user is used to calculate her position, *i.e.* the coordinates. This problem has been particularly stressed in this thesis with the realization of a system that calculate the direction by means of a magnetic sensor. In this case the following specifications are mandatory:

- during straight walking the direction must be stable;
- the integration drift must not affect the measure between two contiguous alignments by means of other systems.

To meet these specifications the direction estimation:

- has not to be affected by the tilt error introduced by the walking. For this reason tilt compensation algorithms are used to calculate the direction;
- has to be referred to the Geographic reference system. For this reason when the direction is computed utilizing the gyroscope, methods to perform the initial alignment are utilized. In the considered case the direction angle derived from the gyroscope is aligned by means of a compass;
- has to be little affected by soft iron interferences. For this reason when the direction is computed utilizing the magnetic sensor, methods to perform the control of magnetic interferences are utilized, for example utilizing the combination between the directions computed from the magnetic sensor and the gyroscope. In the considered case this problem is not taken into consideration;
- robust calibration techniques must be implemented. This has been stressed in this thesis.

Common to the above mentioned points is the necessity to calibrate the sensors in an easy and robust way, and the necessity of estimate how frequently (in term of space or time) the alignment has to be performed by means of other systems.

9.1.1 Straight Walk

To highlight the above mentioned issues the following tests are performed: the user is oriented in a fixed direction and walks straight for 60 meters.

9.1.1.1 Using A One Axis Gyroscope And A Two Axes Accelerometer

In this case the Yaw value for a 60 straight meters is reported, without initial alignment, *i.e.* the value is not referred to the Geographical North.

Mean Value	Variance	Standard Deviation
301,699	12,83516275	3,582619538
108,4379412	15,89263152	3,986556348
272,6015493	12,46232185	3,53020139
85,67058824	14,76128622	3,842041933

Table 9. 1

9.1.1.2 Using A Two Axes Magnetic Sensor And A Three Axes Accelerometer

In this case the Azimuth value for a 60 straight meters is reported, computed by means of the magnetic compass. The value of the orientation is referred to the Geographical North.

Mean Value	Variance	Standard Deviation
158,1393443	21,39295009	4,625251354
4,23	29,82010256	5,460778568
155,13125	53,58629167	7,320265819
354,1272727	21,68892045	4,657136508
355,6	14,5735	3,817525376
357,4622642	23,50470247	4,848164856
151,2121212	60,55547348	7,781739747
167,2290323	54,27322689	7,367036507
355,8428571	17,60663866	4,196026532
158,78	39,24027273	6,264205674

Table 9. 2

9.1.1.3 Comparison

As it can be seen comparing Table 9. 1 and Table 9. 2, the variance and standard deviation are lower in the former case due to the higher short term stability of the gyroscope with respect to the compass. This was a well known phenomenon nevertheless it is necessary to accurately study the compass behavior to integrate its long term stability in the direction estimation system, to compensate gyroscope’s integral drift.

9.2 Steps Detection Comparison

As seen in Chapter 5, the detection of step occurrences can be utilized to calculate the displacements of the user instead of the classical method of double integrate the accelerations. Motivation regard this choice are exposed in Chapter 5.

The detection of steps is performed trying to detect the acceleration peaks during the walk. This detection relies on user-dependent threshold.

The step detection method taken into considerations is sensitive to the “anomalous” steps, such as slow walking and the first and last step. Also this issues will be highlighted in the following tests.

9.2.1 Fixed Number of Steps

In these tests, the errors in the detection of the steps for little path are highlighted. In these test the user walk in a straight line for a fixed number of steps: 1, 2, 5, 10 steps.

9.2.1.1 Using A One Axis Gyroscope And A Two Axes Accelerometer

In Fig. 9. 1 the comparison between the distribution of the detected steps in the 1, 2, 5 and 10 test is shown. As it can be seen from the statistical distributions, the distributions get better when the number of steps increases. In Fig. 9. 2 the percentage errors with respects to the number of steps measured are reported. As it can be seen the percentage error decreases with the increase of the number of steps. Actually, a little number of steps is mainly affected by the problem on detection of the first and last steps.

The mean value of detected steps is closer to the real value when increasing the number of steps, as can be seen in Table 9. 3.

Steps	Mean Value	Difference	Percentage Difference (%)	Variance	Standard Deviation
1	1,2	0,2	20	0,177777778	0,421637021
2	2,1	0,1	5	0,1	0,316227766
5	5	0	0	0	0
10	10	0	0	0	0

Table 9. 3

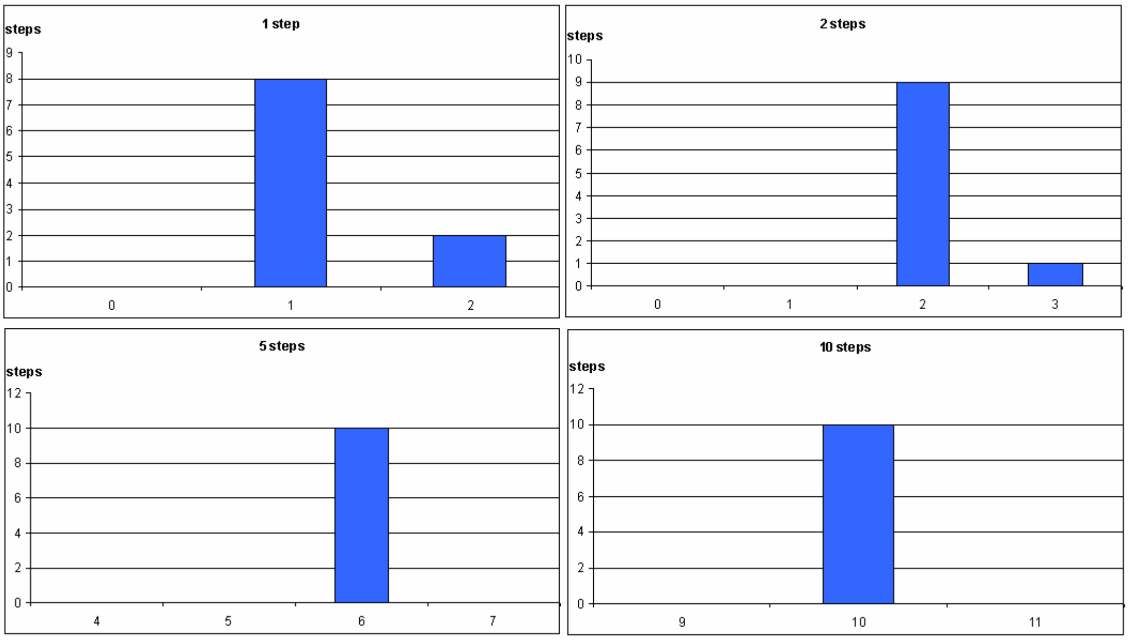


Fig. 9. 1 1-Gyroscope, 2-Accelerometer Statistical distribution of detected steps

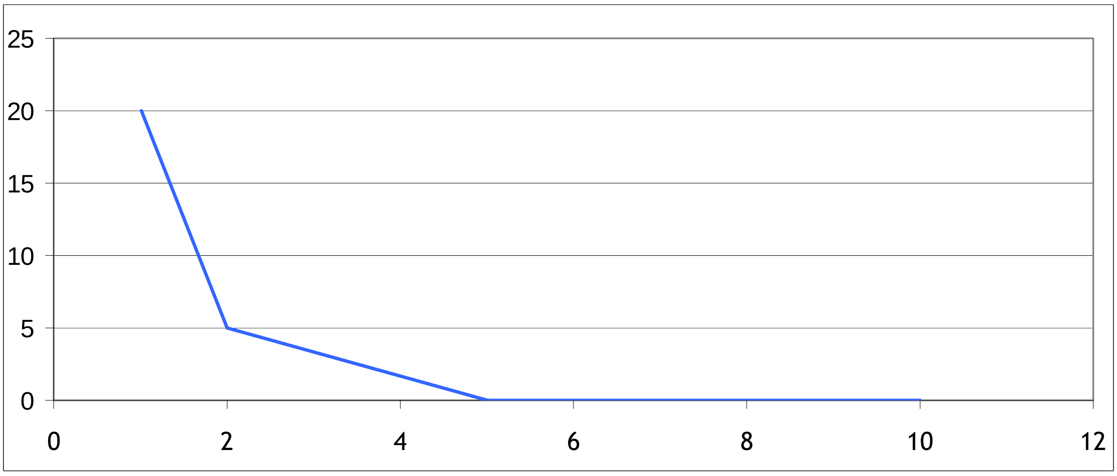


Fig. 9. 2 1-Gyroscope, 2-Accelerometer Percentage errors

9.2.1.2 Using A Two Axes Magnetic Sensor And A Three Axes Accelerometer

These experiments are used also to test the better pouch worn on the belt in which to put the two Pedestrian Navigation systems. In Fig. 9. 3, Fig. 9. 4, Fig. 9. 5 and Fig. 9. 6 the comparison between the distribution of the detected steps in the 1, 2, 5 and 10 test is shown. As it can be seen from the statistical distributions, the black pouch presents the better distribution in all the test except for the Five steps one. The mean value of detected steps is closer to the real value when using the black pouch, as can be seen in Table 9. 4, Table 9. 5, Table 9. 6 and Table 9. 7. For this reason, also in this test and in the other reported tests, the black pouch has been used, although variance and standard deviation are greater than those measured with the green pouch.

In Fig. 9. 7 are reported the percentage errors with respect to the number of steps measured. As it can be seen the percentage error decreases with the increase of the number of steps. In fact, a little number of steps is mainly affected by the problem on detection of the first and last steps.

1 Step	Mean Value	Difference	Percentage Difference (%)	Variance	Standard Deviation
Green	1,2	0,2	20	0,4	0,632455532
Black	1	0	0	0	0

Table 9. 4

2 Steps	Mean Value	Difference	Percentage Difference (%)	Variance	Standard Deviation
Green	1,4	-0,6	-30	0,266667	0,516397779
Black	1,9	-0,1	-5	0,988889	0,994428926

Table 9. 5

5 Steps	Mean Value	Difference	Percentage Difference (%)	Variance	Standard Deviation
Green	4,7	-0,3	-6	0,455556	0,674948558
Black	5,6	0,6	12	0,711111	0,843274043

Table 9. 6

10 Steps	Mean Value	Difference	Percentage Difference (%)	Variance	Standard Deviation
Green	10,3	0,3	3	0,455556	0,674948558
Black	10	0	0	0,444444	0,666666667

Table 9. 7

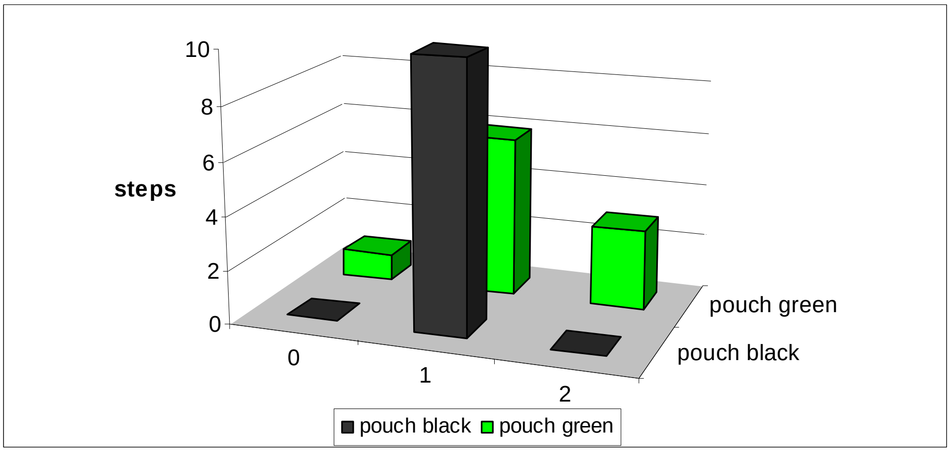


Fig. 9. 3 2-Magnetic Sensor, 3-Accelerometer: One step

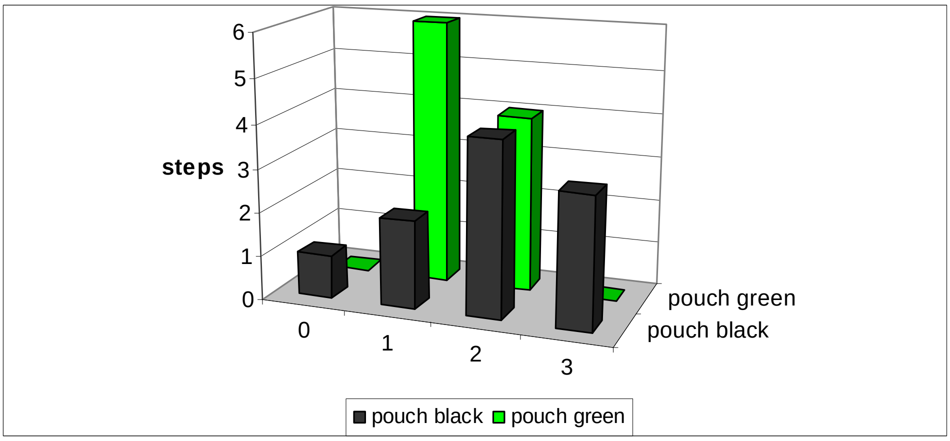


Fig. 9. 4 2-Magnetic Sensor, 3-Accelerometer: Two steps

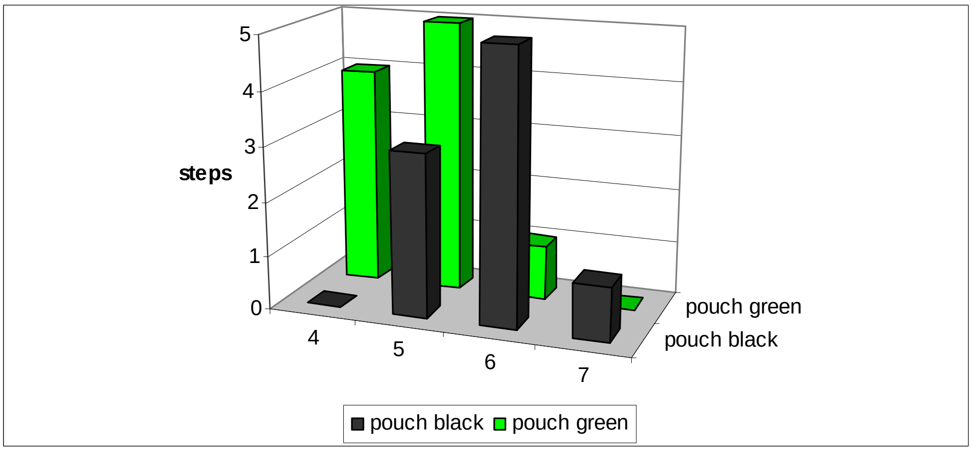


Fig. 9. 5 2-Magnetic Sensor, 3-Accelerometer: Five steps

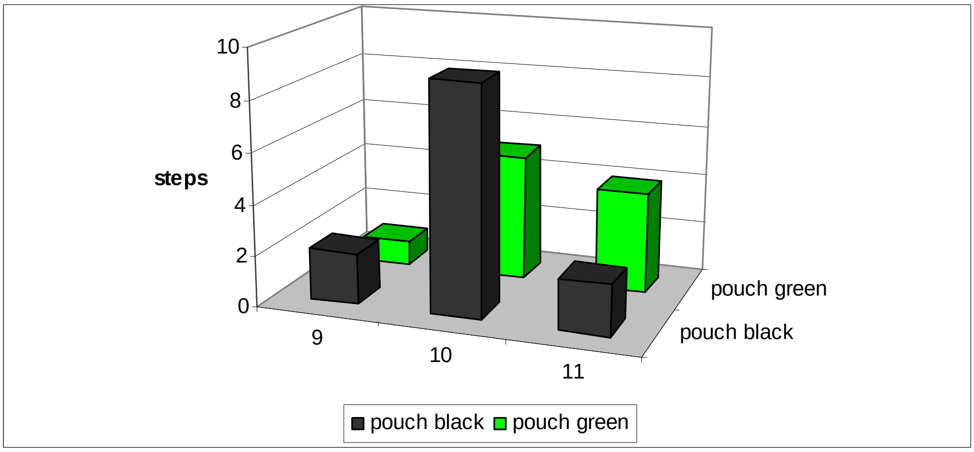


Fig. 9. 6 2-Magnetic Sensor, 3-Accelerometer: Ten steps

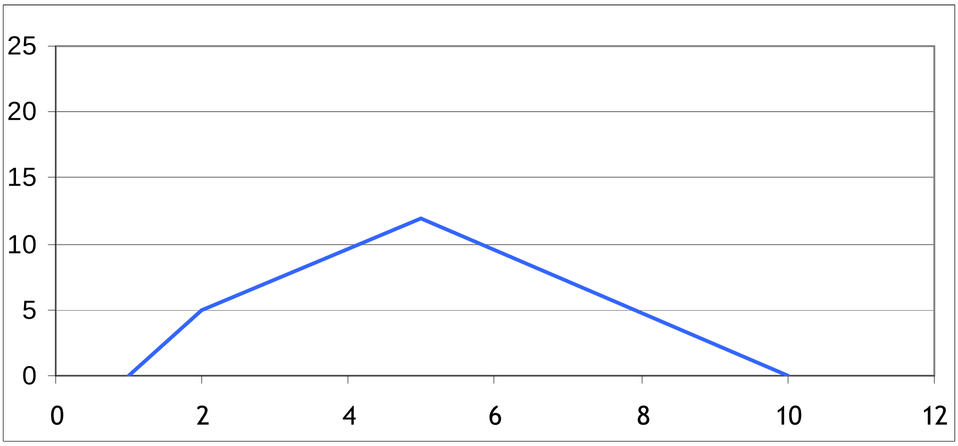


Fig. 9. 7 2-Magnetic Sensor, 3-Accelerometer Percentage errors

9.2.1.3 Comparison

In Table 9. 8 the step detection error of the two step detection algorithms in the case of fixed steps is summarized. The algorithm which uses 1-Gyroscope, 2-Accelerometer is indicated with 1, the 2-Magnetic Sensor, 3-Accelerometer is indicated with 2. The two algorithms are explained in Chapter 8. The first utilizes only the frontal acceleration and the second used the vertical and the frontal acceleration. The first one is utilized in several museum application navigation.

In the Table are compared the results utilizing the black pouch for the tests.

As seen from the Table, the second algorithm provides better mean and variance in the case of one step. With the increase of the number of steps, the first algorithm provides better means and variances. In the case of ten steps, both the algorithm provide an exact mean, but the second has a variance that is non null.

Steps	Mean Value		Difference	Percentage Difference (%)	Variance	Standard Deviation
1	1	1,2	0,2	20	0,177777778	0,421637021
	2	1	0	0	0	0
2	1	2,1	0,1	5	0,1	0,316227766
	2	1,9	-0,1	-5	0,988889	0,994428926
5	1	5	0	0	0	0
	2	5,6	0,6	12	0,711111	0,843274043
10	1	10	0	0	0	0
	2	10	0	0	0,444444	0,666666667

Table 9. 8

9.2.2 Fixed Straight Path

In these tests, the errors in the detection of the steps for medium path length is highlighted. In these test the user walk in a straight line for 60 meters.

9.2.2.1 Using A One Axis Gyroscope And A Two Axes Accelerometer

In Table 9. 9 the results of ten 60 meters straight walks are reported. Due to the increased number of steps, the mean error percentage fall down to 0,4% (Table 9. 10). As seen in the Table, the number of steps detected is always higher than the true value. This can be explained through thresholds setting too much sensitive to the spurious accelerations for this specific user, that brings false positives especially during the first and the last steps.

Start	Stop	Detected Steps	True Steps	Difference (Detected-True)	Error percentage (%)
30	108	78	78	0	0
108	185	77	77	0	0
185	264	79	78	1	1,265822785
266	344	78	78	0	0
705	782	77	77	0	0
784	863	79	78	1	1,265822785
865	945	80	79	1	1,25
947	1023	76	76	0	0

Table 9. 9

Mean error percentage (%)	Mean error	Error Variance	Error Standard Deviation
0,480769231	0,375	0,267857	0,51754917

Table 9. 10

9.2.2.2 Using A Two Axes Magnetic Sensor And A Three Axes Accelerometer

The results of ten 60 meters straight walks are reported. Due to the increased number of steps, the mean error percentage fall down to the 2,6% (Table 9. 12). As seen in the Table the number of steps detected is always higher than the true value. This is can be explained through thresholds setting too much sensitive to the spurious accelerations for this specific user, that brings false positive especially during the first and the last steps.

Start	Stop	Detected Steps	True Steps	Difference (Detected-True)	Error percentage (%)
266	339	73	72	1	1,369863014
339	410	71	71	0	0
410	482	72	72	0	0
482	558	76	71	5	6,578947368
558	631	73	71	2	2,739726027
631	703	72	70	2	2,777777778
703	776	73	71	2	2,739726027
776	850	74	71	3	4,054054054
850	921	71	71	0	0
921	995	74	70	4	5,405405405

Table 9. 11

Mean error percentage (%)	Mean error	Error Variance	Error Standard Deviation
2,606310014	1,9	2,988888889	1,728840331

Table 9. 12

9.2.2.3 Comparison

In Table 9. 13 are summarized the step detection error of the two step detection algorithms. The two algorithms are explained in Chapter 8.

	Mean error percentage (%)	Mean error	Error Variance	Error Standard Deviation
1	0,480769231	0,375	0,267857	0,51754917
2	2,606310014	1,9	2,988888889	1,728840331

Table 9. 13

9.2.3 Fixed Non-Straight Path

During non-straight walk, the accelerations are affected by the centrifugal and tangential acceleration. This can influence the steps detection. In these test, the user follows a fixed non-straight path.

9.2.3.1 Using A One Axis Gyroscope And A Two Axes Accelerometer

In Table 9. 14 the results of ten 50 meters non-straight walks are reported. As seen, the number of steps detected is sometimes higher and sometimes lower than the true value.

Due to the non-straight path the mean error percentage rise to 0,6 % with respects to the straight path (Table 9. 15).

Start	Stop	Detected Steps	True Steps	Difference (Detected-True)	Error percentage (%)
529	594	65	66	-1	-1,538461538
594	658	64	65	-1	-1,5625
659	724	65	65	0	0
738	803	65	65	0	0
803	867	64	64	0	0
867	932	65	65	0	0
934	998	64	65	-1	-1,5625
998	1063	65	65	0	0
1063	1129	66	65	1	1,515151515
1129	1193	64	64	0	0

Table 9. 14

Mean Error Percentage (%)	Mean Error	Error Variance	Standard Deviation
-0,309119011	-0,2	0,4	0,632455532

Table 9. 15

9.2.3.2 Using A Two Axes Magnetic Sensor And A Three Axes Accelerometer

In Table 9. 16 the results of ten 50 meters non-straight are reported. As seen in the Table, the number of steps detected is always higher than the true value. This is can be explained through thresholds setting too much sensitive to the spurious accelerations for this specific user, that brings false positive especially during the first and the last steps.

Due to the non-straight path the mean error percentage rise to 4,9% with respects to the straight path (Table 9. 15).

Start	Stop	Detected Steps	True Steps	Difference (Detected-True)	Error percentage (%)
73	141	68	66	2	2,941176471
141	207	66	65	1	1,515151515
211	280	69	65	4	5,797101449
280	343	63	63	0	0
343	413	70	65	5	7,142857143
413	483	70	65	5	7,142857143
483	553	70	65	5	7,142857143
554	620	66	65	1	1,515151515
621	692	71	64	7	9,85915493
696	765	69	65	4	5,797101449

Table 9. 16

Mean Error Percentage	Mean Error	Error Variance	Standard Deviation
4,985337243	3,4	5,155555556	2,270584849

Table 9. 17

9.2.3.3 Comparison

In Table 9. 18 are summarized the step detection error of the two step detection algorithms in the case of non-straight walk.

Mean error percentage (%)	Mean error	Error Variance	Error Standard Deviation
0,618238022	-0,2	0,4	0,632455532
4,985337243	3,4	5,155555556	2,270584849

Table 9. 18

9.2.4 Female User

It is known in literature that the detection of steps for female user is an open issue. In particular, from previous works, it is known that the first algorithm detects fewer steps with respect to the real. To better evaluate the behavior of the second algorithm (which uses the vertical and the horizontal accelerations), in the following results are shown ten straight walk of 10 steps each, when the user is a woman.

In Table 9. 19 the results of the ten tests are reported. As it can be seen, the detected value is not always less than the true one, but it is often higher. This demonstrate that the second algorithm has not also misdetections.

In Table 9. 20 is reported the mean error percentage. This is higher (4,7%) with respect to the mean error percentage in the case of male user which is 4% (Paragraph 9.2.1.2).

In Fig. 9. 8 the second steps detection algorithm in the case of female and male user are compared. As seen, the distribution for the female user has a greater variance.

The problem of the detection of female user is an open issue which has to be investigated in the future even though these first results, so similar to the male ones, are encouraging.

Start	Stop	Detected Steps	True Steps	Difference (Detected-True)	Error percentage (%)
15	25	10	10	0	0
25	35	10	10	0	0
35	46	11	10	1	9,090909091
46	57	11	10	1	9,090909091
57	68	11	10	1	9,090909091
68	80	12	10	2	16,66666667
80	91	11	10	1	9,090909091
91	101	10	10	0	0
101	111	10	10	0	0
111	120	9	10	-1	11,11111111

Table 9. 19

	Mean Error Percentage (%)	Mean Error	Error Variance	Standard Deviation
Female	4,761904762	0,5	0,722222222	0,849836586
Male	4	0,4	0,266667	0,516398

Table 9. 20

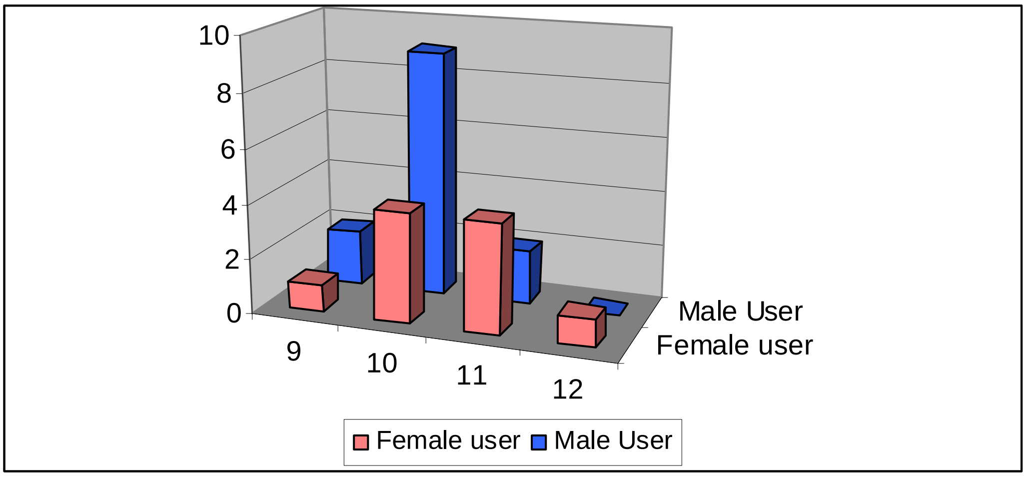


Fig. 9. 8 Female vs. Male Steps Detection Distribution

9.3 Steps Length

As seen in Chapter 5, to calculate the displacements of the user utilizing the step detection, methods to calculate the step length are used.

The step length calculation is performed in these two cases utilizing an empirical formula which depend on a multiplicative parameter (see Chapter 5) which varies from 0 to 1. This parameter (K) depends on the user. To show the good quality of the method, results of a 60 meters straight line are shown, utilizing a fixed value for the K parameter (K=0,95). Since the step length of a user is not fixed, in this tests is calculated the error on the detected distance computed as the sum of the step length. This test is used also as an indication of positioning in the case of straight walk.

Utilizing the step length and the total fixed distance an iterative method to calculate the K parameter for a specific user should be created: the medium step length is calculated and the K value which should be used in order to have a distance calculation of 60 meter is computed. In this case any error that should occur has been manually removed.

In this case the two Pedestrian Navigation system are compared: the first method compute the step length using the frontal acceleration, the second method compute the step length using the vertical acceleration

9.3.1.1 Using the Frontal Acceleration

In Table 9. 21 the K values of each tests are reported. In Table 9. 22 their mean value, variance and standard deviation are shown. Using this statistically found K, distance values are recalculated in Table 9. 23. Using this mean K value, the mean total distance of the walk is computed (Table 9. 24). Of course, this value is very close to the true value. What is more interesting, the variance and the standard deviation give a precious information about the error not dependent on the user and tha can not be eliminated thought the compensation process.

K
0,982
0,979
0,989
0,972

Table 9. 21

Mean Value	Variance	Standard Deviation
0,9805	0,00005	0,007047458

Table 9. 22

Calculated distance with mean K
60,52574895
59,48538684
60,09329684
59,95189842

Table 9. 23

Mean Value	Variance	Standard Deviation
60,01408276	0,183821141	0,428743678

Table 9. 24

9.3.1.2 Using the Vertical Acceleration

In Table 9. 25 the K values of each tests are reported. In Table 9. 26 their mean value, variance and standard deviation are shown. Using this statistically found K, distance values are recalculated in Table 9. 27. Using this mean K value, the mean total distance of the walk is computed (Table 9. 28). Of course, this value is very close to the true value. What is more interesting, the variance and the standard deviation give a precious information about the error not dependent on the user and can not be eliminated thought the compensation process. Since this error depends on the architecture characteristics it can be eliminated only through the design improvement, thus it is a focus topic for further research.

K
0,945
0,939
0,967

0,942
0,971
0,93
0,935
0,965
0,927
0,975

Table 9. 25

Mean Value	Variance	Standard Deviation
0,9496	0,000326933	0,018081298

Table 9. 26

Calculated distance with mean K
60,2996
60,72142232
58,97715705
60,52050695
58,68627958
61,32116968
60,95132547
59,05812295
61,56106863
58,49036211

Table 9. 27

Mean Value	Variance	Standard Deviation
60,05870147	1,319147992	1,148541681

Table 9. 28

9.3.1.3 Comparison

In Table 9. 29 are compared the two statistical descriptions of the boards. In the last column it is reported the standard deviation percentage. Walking for 100 meters, the first method is expected to be affected by an average error of 0,7 meters; the second method is expected to be affected by an average error of 1,9 meters.

	Mean Value	Variance	Standard Deviation	Standard Deviation %
1	60,05870147	1,319147992	1,148541681	0,714405
2	60,01408276	0,183821141	0,428743678	1,912365157

Table 9. 29

9.4 Positioning

The direction, the step detection and the step length are used to compute the position of a user. The results regarding the merging of these data are highlighted in this Paragraph for a closed loop walk. This walk has a total length of 50 meters and the starting point coincides with the finish point. In Fig. 9. 9 is reported the shape of the walk with the measure of the single straight paths. The red dot represent the starting and the finish point. The arrow indicate the sense in which the path is walked. In the following paragraphs are reported the results about ten walks around the path, in the case of the two different approaches.

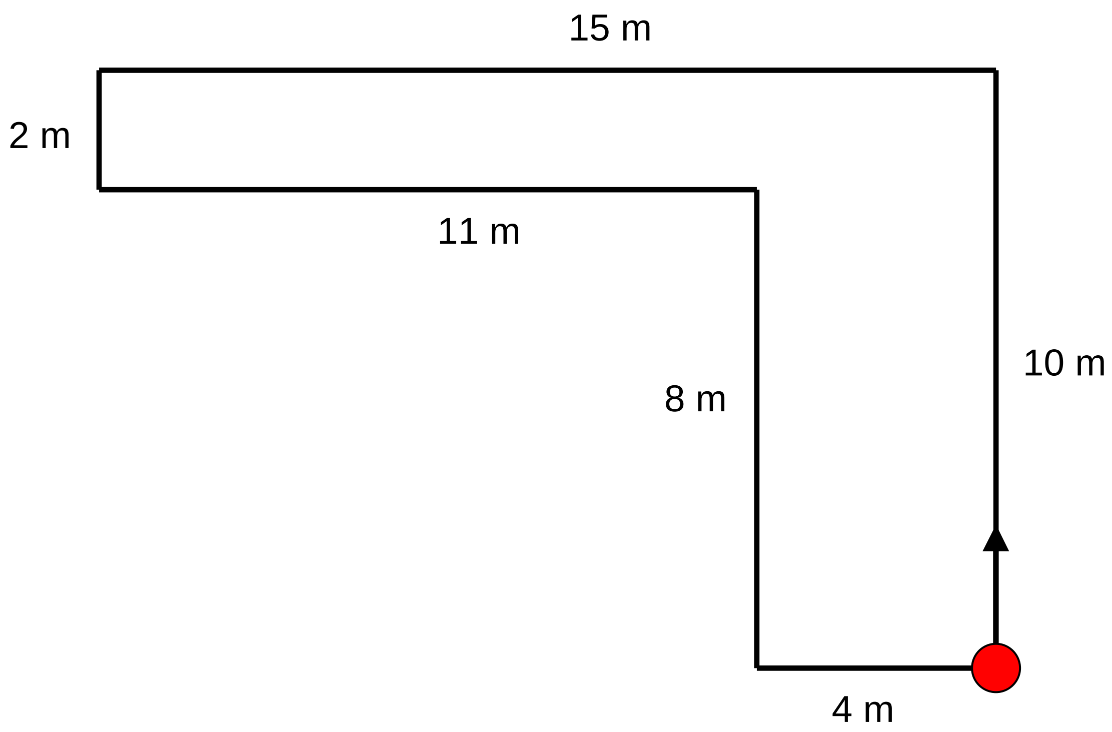


Fig. 9. 9 Composed and closed walk

9.4.1 Using A One Axis Gyroscope And A Two Axes Accelerometer

In Table 9. 30 the difference between the computed coordinates of the starting and finish points are reported. The total gap between the two points is also shown. As it can be seen, this has a maximum value of 1,5 meters and a minimum value of 0,4 meters.

Fig. 9. 10 and in Fig. 9. 11 show respectively the best and the worst calculated path.

X	Y	Gap
-0,125	-0,387	0,406686612
-1,091	-0,519	1,208156447
-1,099	-0,126	1,106199349
-1,217	-0,432	1,291399628
-0,665	-0,805	1,044150372
-1,513	-0,118	1,517594478
-0,723	-0,016	0,723177018
-0,824	-0,968	1,271219887
-1,125	-0,506	1,233556241
-0,451	-0,602	0,752200106

Table 9. 30

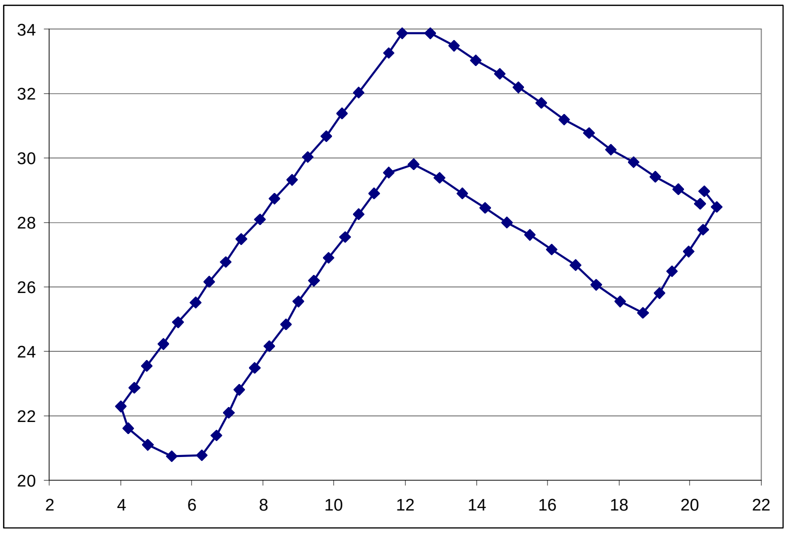


Fig. 9. 10 1-Gyroscope, 2 Accelerometer, Best Positioning Path

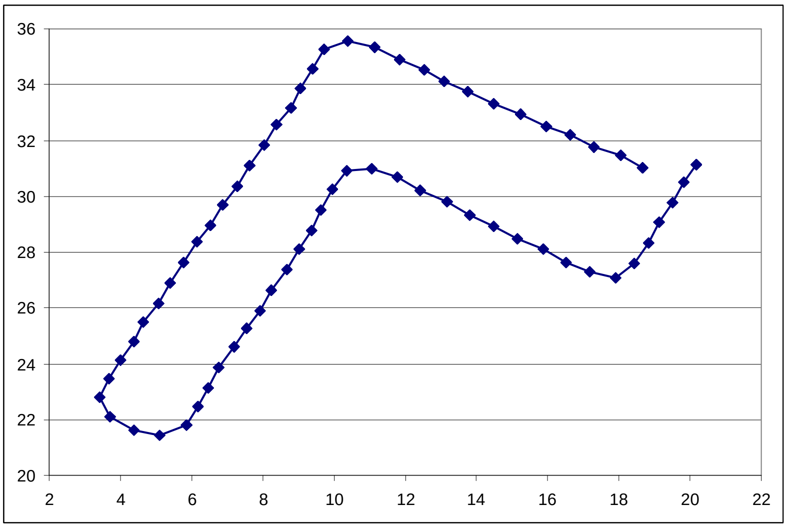


Fig. 9. 11 1-Gyroscope, 2 Accelerometer, Worst Positioning Path

9.4.2 Using A Two Axes Magnetic Sensor And A Three Axes Accelerometer

In Table 9. 31 the difference between the computed coordinate of the starting and finish points are reported. The total gap between the two points is also shown. As it can be seen, this has a maximum value of 10 meters and a minimum value of 4,8 meters.

Fig. 9. 12 shows the best calculated path.

X	Y	Gap
5,300	-3,000	6,090
6,900	-4,400	8,184
6,500	-5,700	8,645
6,300	-4,900	7,981
7,300	-6,800	9,976
6,400	-6,200	8,911
7,800	-7,300	10,683
-1,500	-4,600	4,838
2,500	-5,500	6,042

Table 9. 31

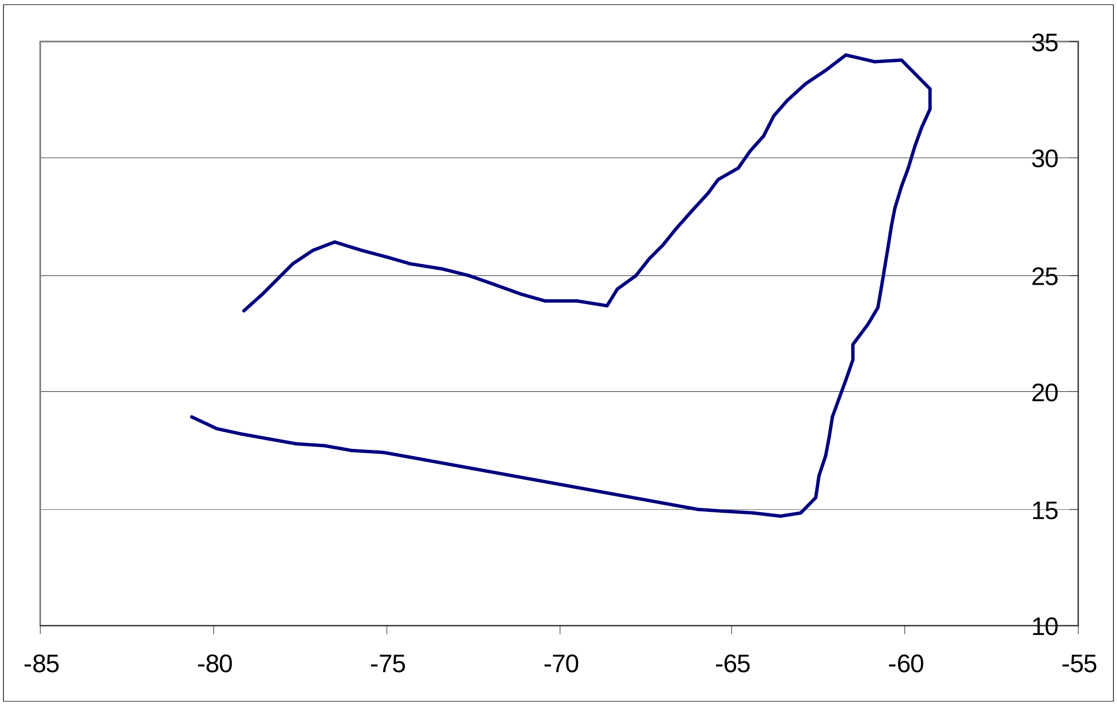


Fig. 9. 12 2-Compass, 3 Accelerometer, Best Positioning Path

9.4.3 Comparison

In Table 9. 32 the comparison between the best cases for the two Pedestrian Navigation systems are reported. As it can be seen, the first provide better performance due to the fact that the first is a mature product, well tested and reliable.

On the other hand the second approach is a recent development that must be further tested. This set of trials can be considered as a first set in this adjustment process, in that some weak points already emerge, *i.e.* high sensitivity to magnetic fields can give birth to severe mismatches between true and detected positions when the device is used in the presence of external magnetic fields; the sensitivity to physiological characteristics of the user, so that K and thresholds settings must be tailored to measure for each user.

	X	Y	Gap
1	-0,125	-0,387	0,406686612
2	-1,500	-4,600	4,838

Table 9. 32

Chapter 10

Conclusions

The research discussed in this thesis was mainly focused on the Smart Environment panorama. This panorama regards several research area, such as Ubiquitous Computing, Pervasive Computing, Ambient Intelligence, and derives much of its inspiration from Weiser's vision (Weiser, 1991). This vision is characterized by the ubiquitous presence of networked computing devices, on the person, in vehicles, in buildings, in consumer products and so on. In this vision these devices should disappear, seamlessly integrated in everyday objects.

Deriving from this vision, in this work Smart Environment has been defined taking into consideration the connection between the physical world and the information world. Several issues and several research areas are involved in the context of the Smart Environments. The exposed research focuses on the following topics:

- the definition of a new vision of Smart Environment
- the creation of a procedure to create a Smart Environment in an easy and automatic way starting from a physical environment
- the study and realization of interaction methods to provide natural interfaces between human and devices
- the study and realization of methods to provide the user's pedestrian localization contextual information.

The first point has been developed within the EU 7th Framework Programme SOFIA (*Smart Object for Intelligent Applications*) project. SOFIA aims at making information in the physical world available for smart services. Functional to this challenge is interoperability at different levels: communication, service and information. SOFIA is the framework in which all this research is contained.

The second and the third points are strictly correlated. To perform any Smart Environment application, with the help of the infrastructures developed within the SOFIA project, the hypothesis of the existence of the Smart Environment must be made. Then, the creation of the Smart Environment starting from an heterogeneous physical environment is the first step to be taken to create an application whatsoever. In this research an innovative, easy, fast and natural way to create Smart Environment starting from physical environment has been studied. This process has developed into a patent. In general, in Smart Environment, devices that are able to connect people and environment within the Smart Environment are called Smart Objects. Then, how the object interact with the user is critical. In particular, the object which permit to create the Smart Environment has to be easy and user-friendly. The design and development of a Smart Object aimed to supply this duty, has been taken into consideration during the PhD period.

The latter point derives from the necessity to extract the contextual data from the environment and from the environment occupants. In fact, as seen, for each entity populating the physical environment, *i.e.* users, objects, devices, sub-parts of the environment, the Smart Environment try to answer to the questions: "*Who*?", *i.e.* which are the entities that should be identified?; "*What*?" *i.e.* which attributes and properties of the entities should be stored in the Smart Space in a machine-understandable format, in the sense that its meaning has to be explicitly defined and all the data should be linked together in order to be automatically retrieved by interoperable applications?; "*Where*?" *i.e.* where such entities are located in physical space?

In this research work in particular the last question has been considered. This question imply that the Smart Environment has to be location-aware, in the sense that it must be able to know the position of mobile entities (*users, objects* and *devices*) at any time. The research has been focused on people location, taking into consideration *Pedestrian Positioning* systems which provide the position of a user which wears them. The comparison between two *Pedestrian Positioning* systems has been exposed. One of these systems has been completely developed during the doctoral period. This calculates the user's orientation utilizing a tilt compensated magnetic compass based on a two-axes magnetic sensor and a three-axes accelerometer. This is a recent development that must be further tested.

The two systems try to meet the *Pedestrian navigation system requirements* which are introduced in the work and exposed in Chapter 5:

- Wearability
- Low Power Consumption
- Testability
- Ease of Calibration
- Orientation
- Relative Position
- Activity Indication
- Wireless Communication

- Semantic Platform Integration
- Azimuth Max Deviation = ±3° when Tilt less than ±30°
- Tracking Error minor of 3% on a 100 m walk in a flat area

In the developed compass based approach particular effort has been made to meet the Easy calibration requirement, creating a user-friendly, simple and robust compass calibrating algorithm.

Regarding the Performance Requirements these are the results of the integration of sensors and algorithms.

Regarding the Azimuth Max Deviation when the system is tilted, in Chapter 7 it has been demonstrated that the error is around 2.5°, when the tilt is below 40° of inclination.

Regarding the displacement in straight path, in Chapter 9 it has been demonstrated that if the user walks for 100 meters the Pedestrian Positioning system is expected to be affected by an standard deviation error of 1,9 meters. This information is particularly important when the system is used as support of navigation systems. In fact, to guarantee that the position of the user do not exceed a fixed error, re-alignment with other system has to be performed.

The Pedestrian Positioning system based on compass shown in this thesis is a recent development that must be further studied. The reported tests can be considered as a first step in this adjustment process, in that some weak point already emerge, *i.e.* high sensitivity to magnetic fields can give birth to severe mismatches between the true and detected positions when the device is used in the presence of external magnetic fields; the sensitivity to physiological characteristics of the user, so that K and thresholds settings must be custom-made for each user.

9.1 Future Developments

In order to improve the performance in Pedestrian Navigation systems using inertial and magnetic sensors, it is essential to provide reliable positioning data. Then, all the steps which are involved in this process has to be considered and improved in performance. These steps are: the estimation of the orientation of the user, the detection of step occurrences and the estimation of the step length. As seen, they are all correlated with each other.

The following topics must be investigated:

- the steps detection algorithm must take into consideration the problem of first and last steps. Moreover, the detection of “anomalous” steps, such as slow walk or lateral steps must be considered;
- the step detection algorithm and the step length algorithm depends on threshold and multiplicative factor which depend on the user. Simple and universal calibration methods for this parameters has to be studied and implemented

- to diminish the errors due to integration drift for the gyroscopes and the errors due to spurious magnetic field in the magnetic sensors the integration between the two sensors has to be investigated, also adding other sensors. Actually, redundant methods to perform the orientation calculation can be used. For example utilizing the integration of a three-axes compass and a three-axes gyroscope: by means of the compass the Dip Angle can be continuously computed; when the computed Dip Angle is different from the Dip Angle deriving from the calibration process, it can be supposed that the compass is in presence of spurious electromagnetic field. In this case the calculation of the position using the compass is not considered valid, and can be computed using the gyroscope;
- to test the functioning in the “real” walking conditions, up and down stairs tests, and upward and downward test has to be performed.

PUBLICATIONS

Publications and Public Presentations

"*CIMAD - A Framework for the Development of Contest-aware and Multi-channel Cultural Heritage Services*" G. Raffa, P. H. Mohr, N. Ryan, D. Manzaroli, M. Pettinari, L. Roffia, S. Bartolini, L. Sklenar, F. Garzotto, P. Paolini, T. Salmon Cinotti - ICHIM07, 2007 Toronto

"*A Stereo Vision based system for advanced Museum services*" M. Pettinari, D. Manzaroli, S. Bartolini, L. Roffia, G. Raffa, L. Di Stefano, T. Salmon Cinotti, edited by David Pletinckx, Workshop Proceedings, Page(s): 57 - 68, Ed. ARCHAEOLINGUA

"*Interoperable multimedia mobile services in cultural heritage sites*" N. Ryan , P. Mohr, D. Manzaroli, G. Mantovani, S. Bartolini, A. D'Elia, M. Pettinari, L. Roffia, L. Sklenar, F. Garzotto, T. Salmon. EPOCH Conference on Open Digital Cultural Heritage Systems (2008)

"*Technology meets Culture: from MUSE to EPOCH*", Tullio Salmon Cinotti, Marina Pettinari, Luca Roffia, Daniele Manzaroli, Sara Bartolini "Atti del Convegno Internazionale Vesuviana. Archeologie a confronto, Bologna, 14-16 gennaio 2008, a cura di Antonella Coralini, Bologna, Edizioni Antequem (in corso di stampa).

"*Personalized Context Based Services for Dynamic User Groups*" L. Roffia, L. Lamorte, G. Zamagni, S. Bartolini, A. D'Elia, F. Spadini, D. Manzaroli, C. A. Licciardi, T. Salmon Cinotti, STWiMob'2009, October 12, 2009) in conjunction with WiMob-2009, Marrakech, Morocco

"*Approaching the design of Interoperable Smat Environment Applications*" F.Spadini, S. Bartolini, R. Trevisan, G. Zamagni, A. D'Elia, F. Vergari, L. Roffia, T. Salmon Cinotti, 2nD International NoTa Conference, 2009, San Jose, CA, USA

"*Abstracting Knowledge from Physical Parameters in Smart Spaces:A Smart M3 Demonstration*" J. Honkola, H. Laine, F. Spadini, F. Vergari, G. Zamagni, S. Bartolini, R. Trevisan A. D'Elia, L. Roffia, D. Manzaroli, C. Lamberti, T. Salmon Cinotti,, 2nD International NoTa Conference, 2009 San Jose, CA, USA

"*First interoperability demo with two indipendent Smart Spaces (aligning was performed by a dedicated KP)*" Eurotech, Nokia, VTT, UnBo: P. Azzoni, J. Honkola, T. Salmon Cinotti, J-P Soininen and their teams, 1st ARTEMIS AUTUMN event 2009, Madrid

"A Smart Space Application to Dynamically Relate Medical and Environmental Information" F. Vergari, S. Bartolini, F.Spadini, A. D'Elia, G. Zamagni, L. Roffia, T. Salmon Cinotti
European Event for Electronic System Design and Test Date2010 (Dresden, Germany, March 8-12, 2010)

Chapter proposal

"Handbook of Research on Technologies and Cultural Heritage"
Edited by Dr. Georgios Styliaras, Dr. Dimitrios Koukopoulos and Dr. Fotis Lazarinis of the University of Ioannina

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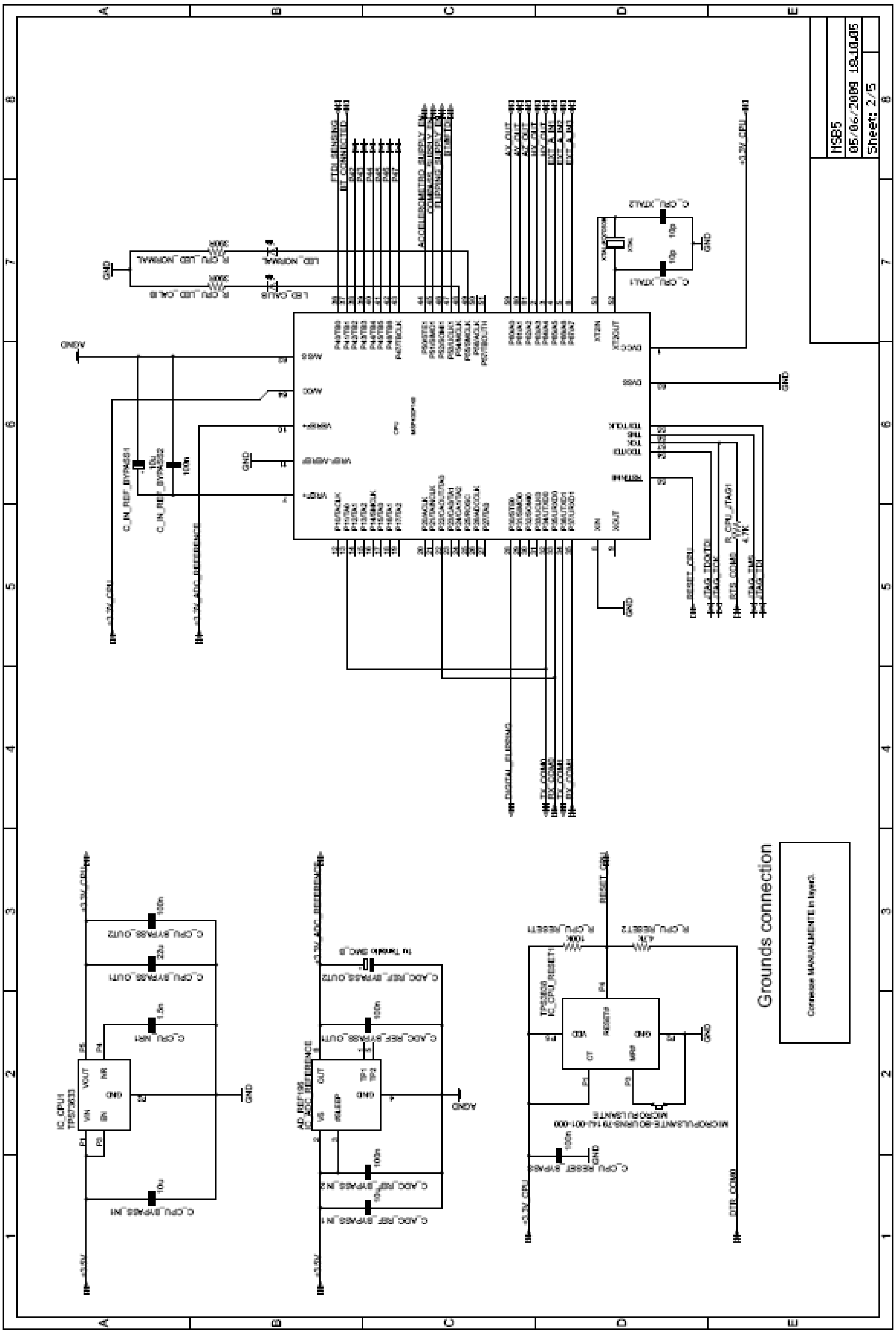
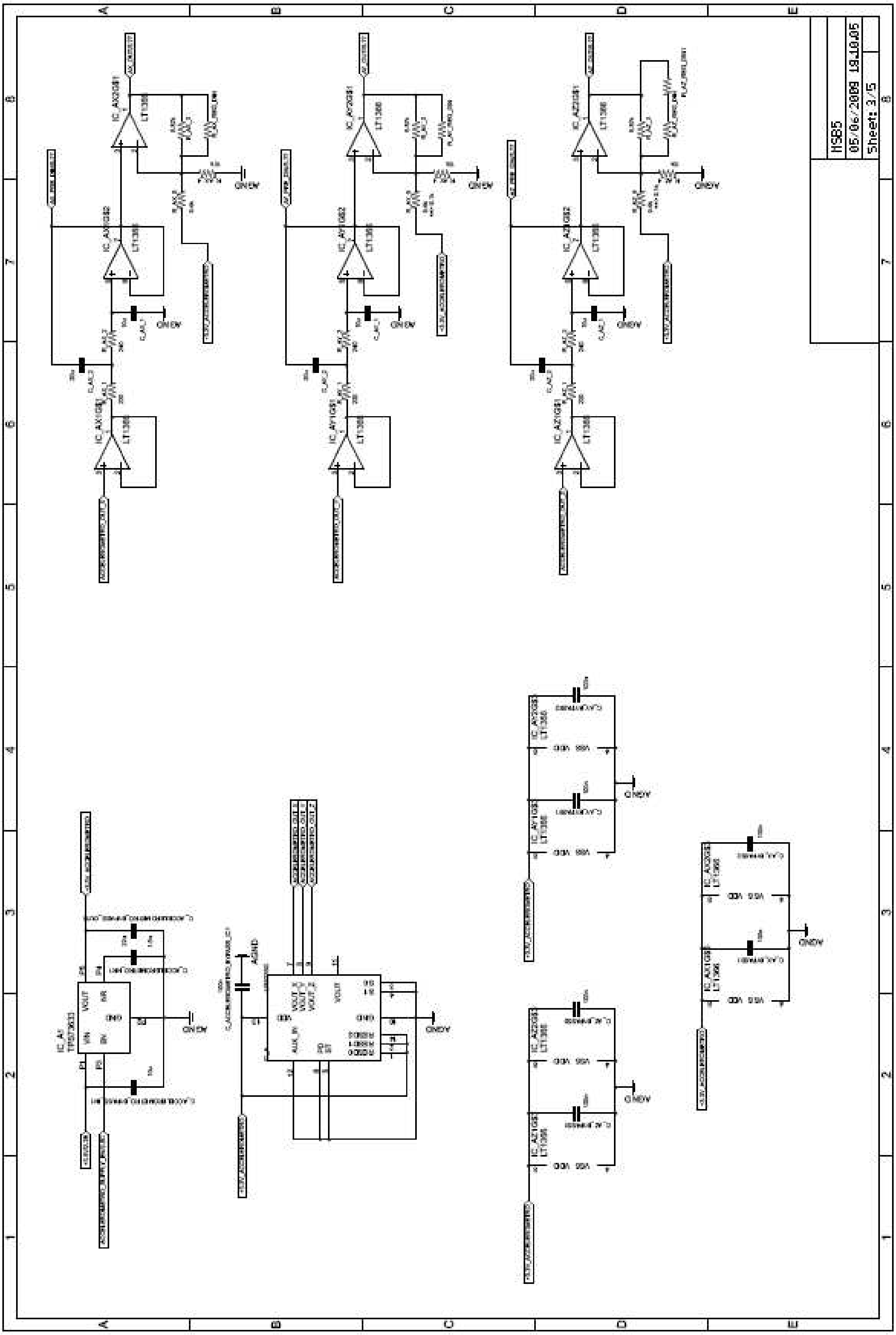
Appendix A

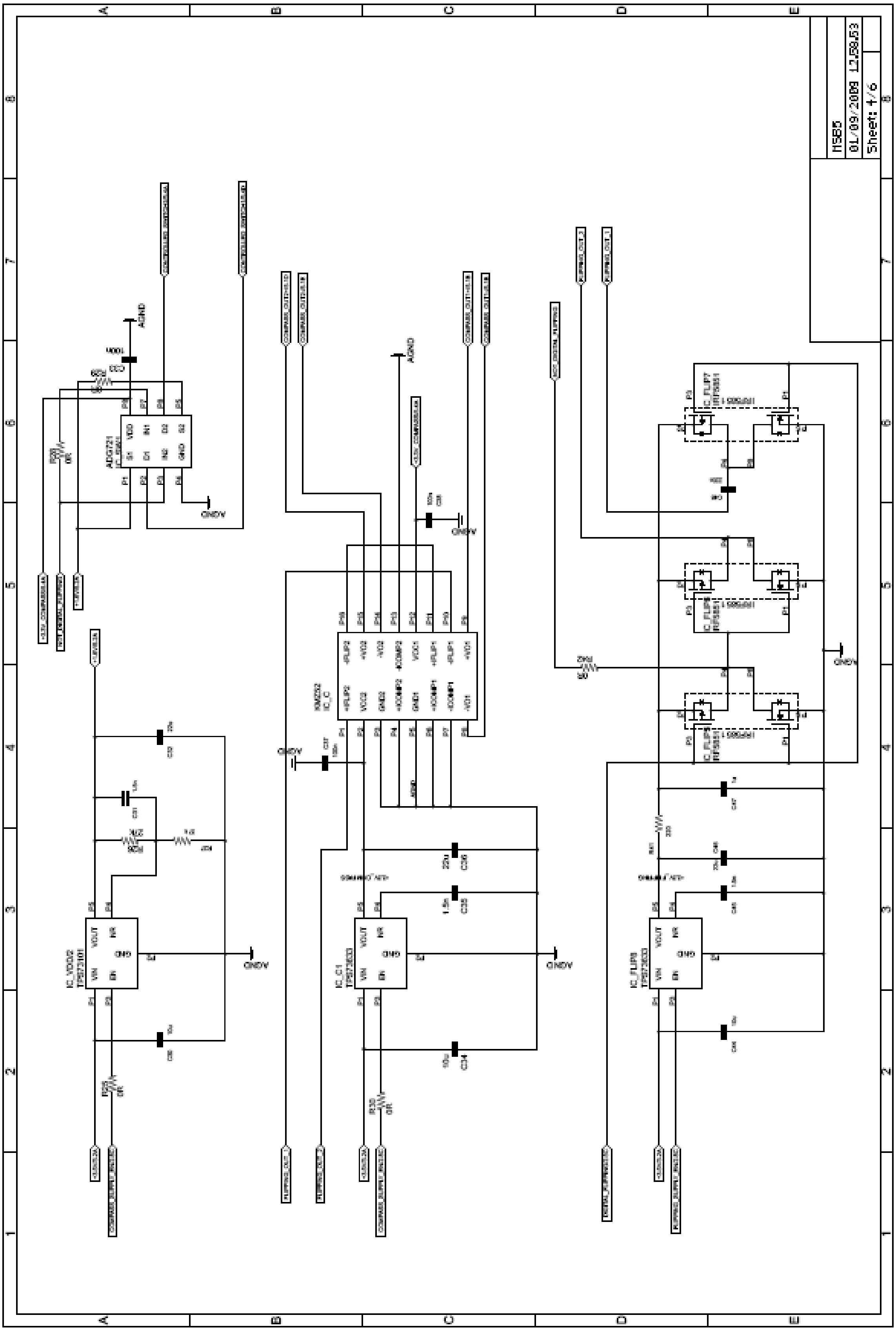
Microcontroller



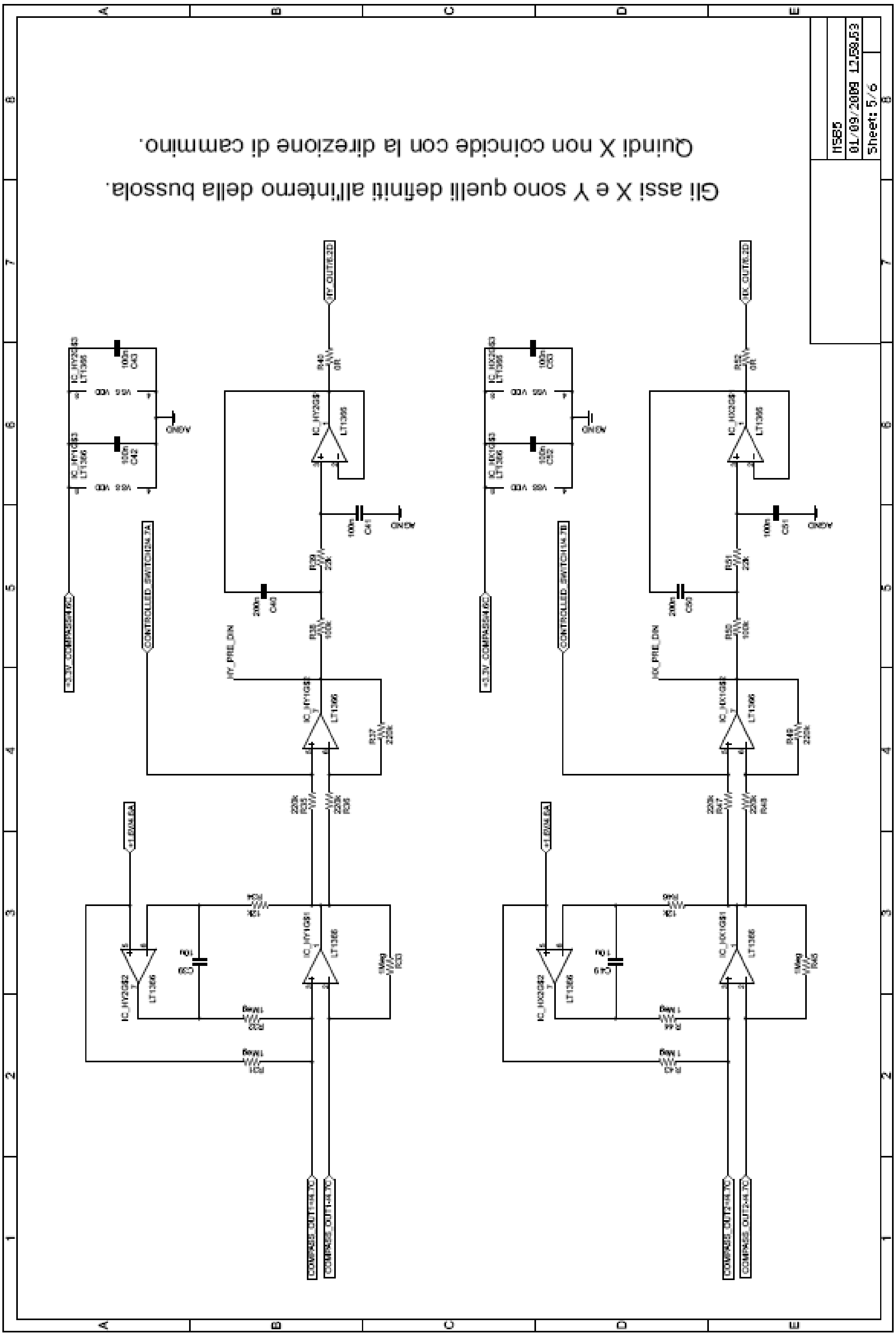
Accelerometer and Accelerometer Conditioning Chain



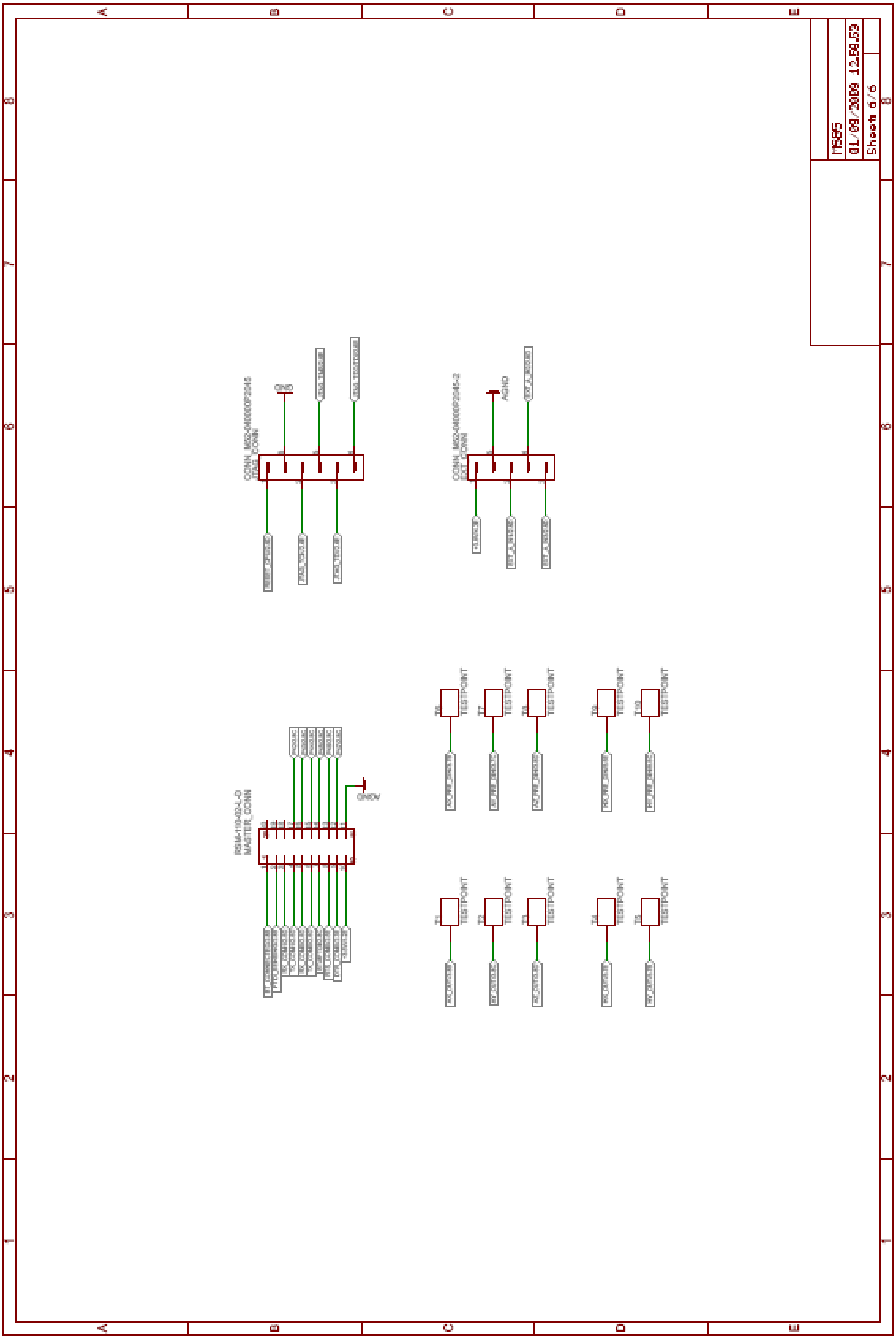
Compass



Compass Conditioning Chain

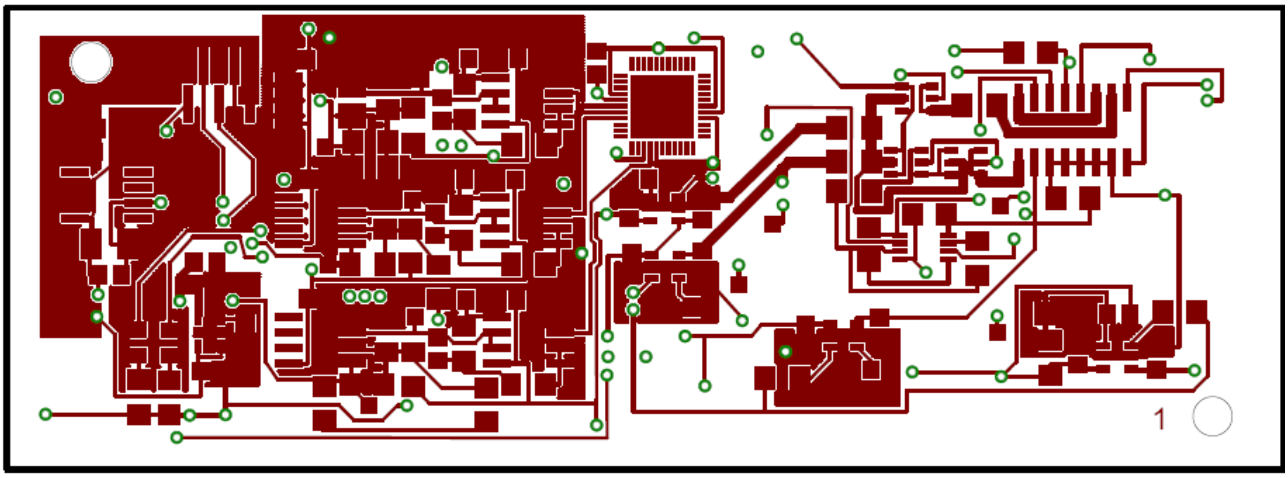


Connectors

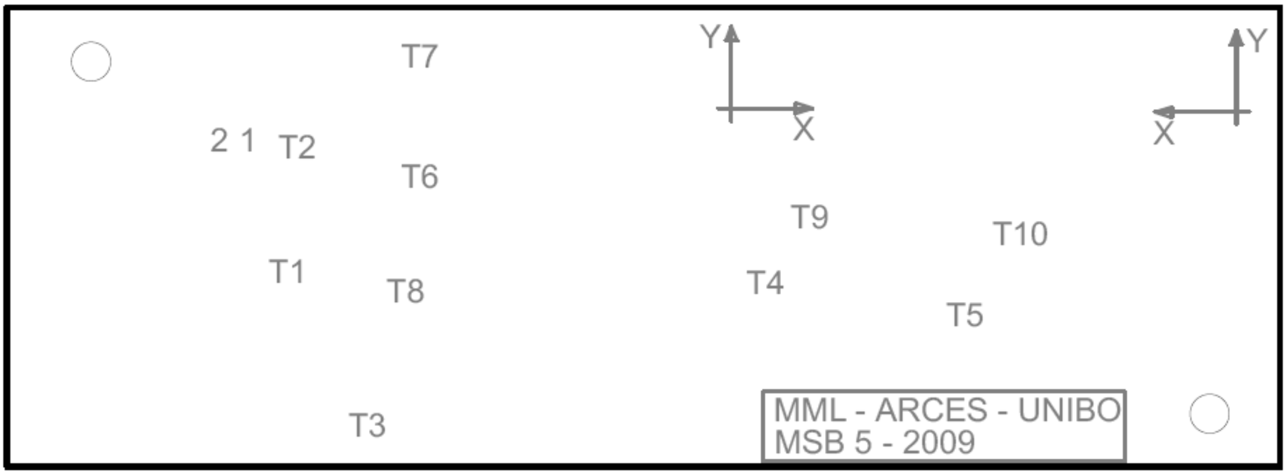


Appendix B

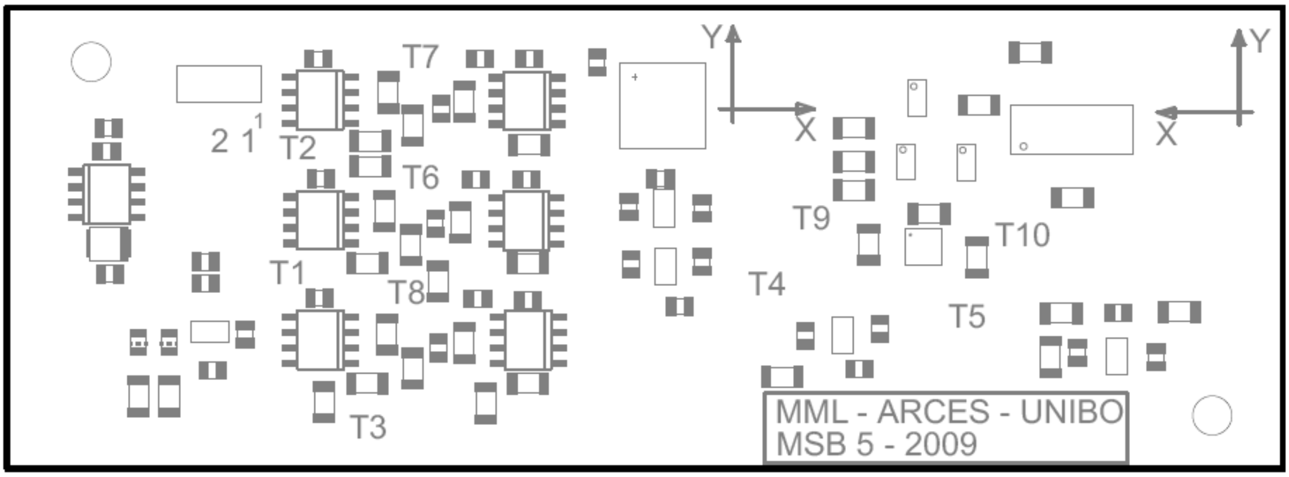
Top Copper



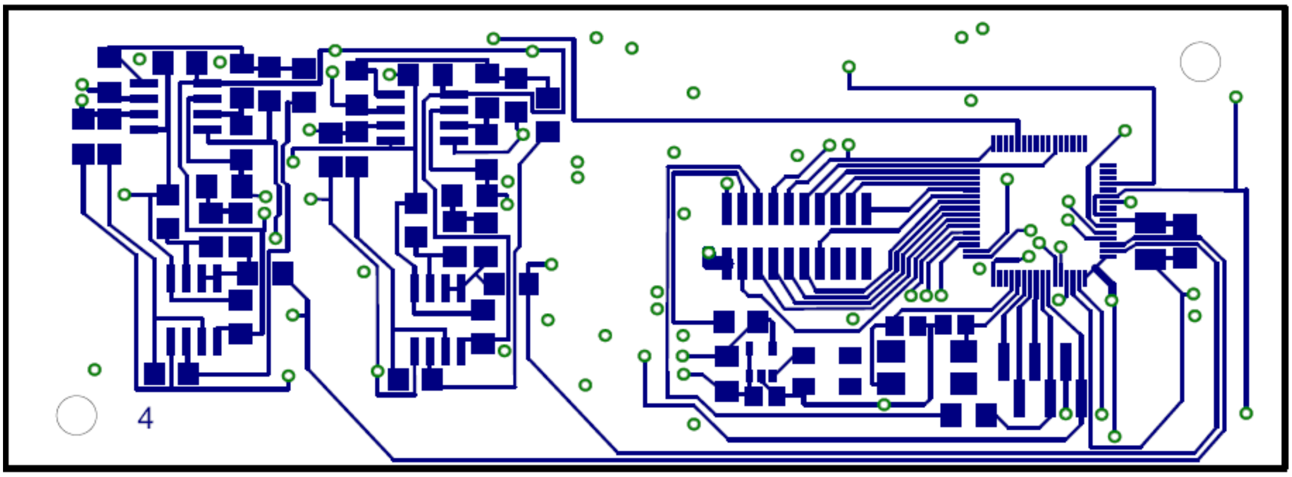
Top Screen_printing



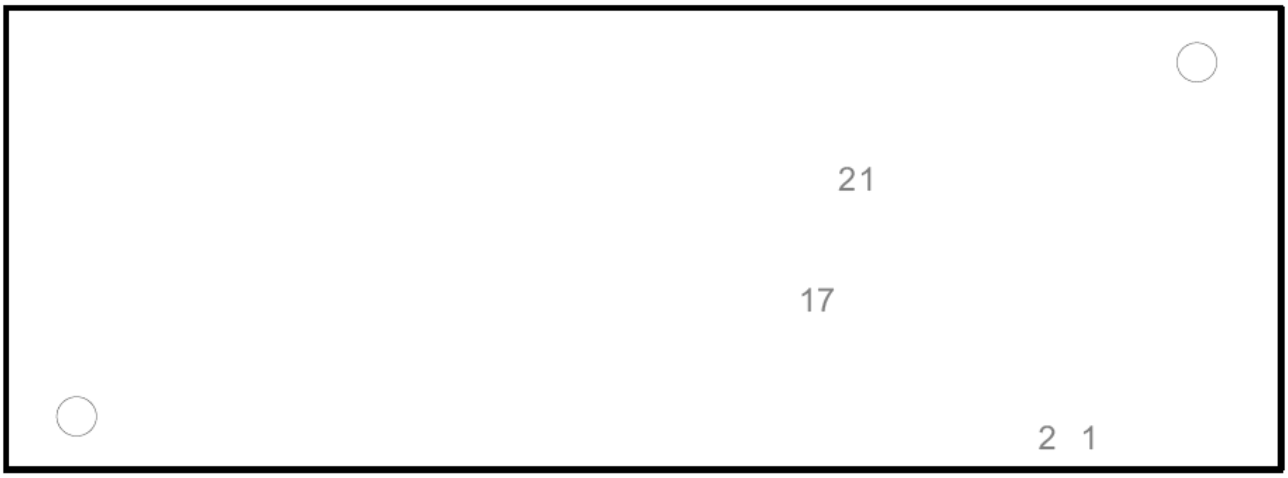
Top Screen_printing and Components



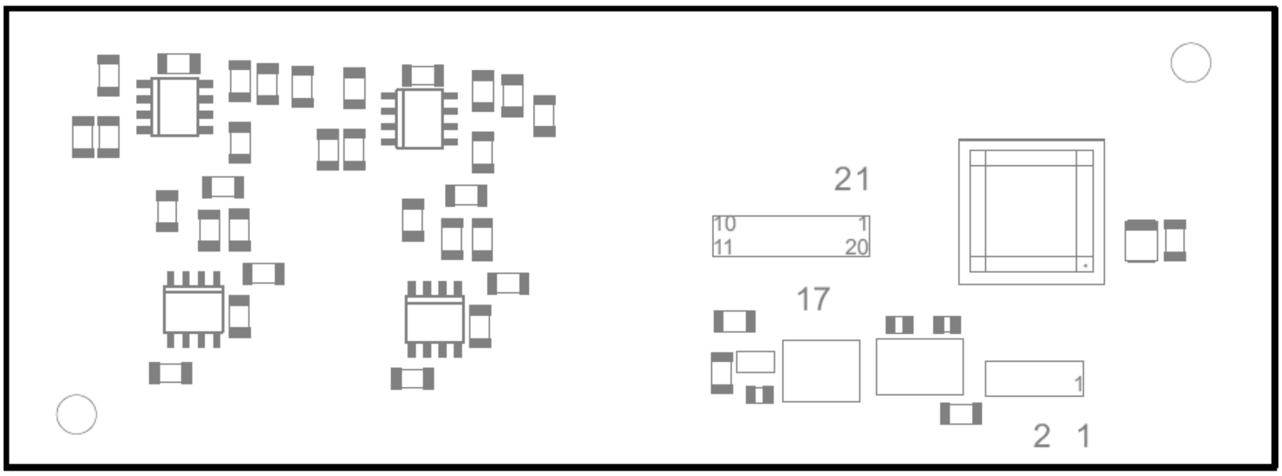
Bottom Copper



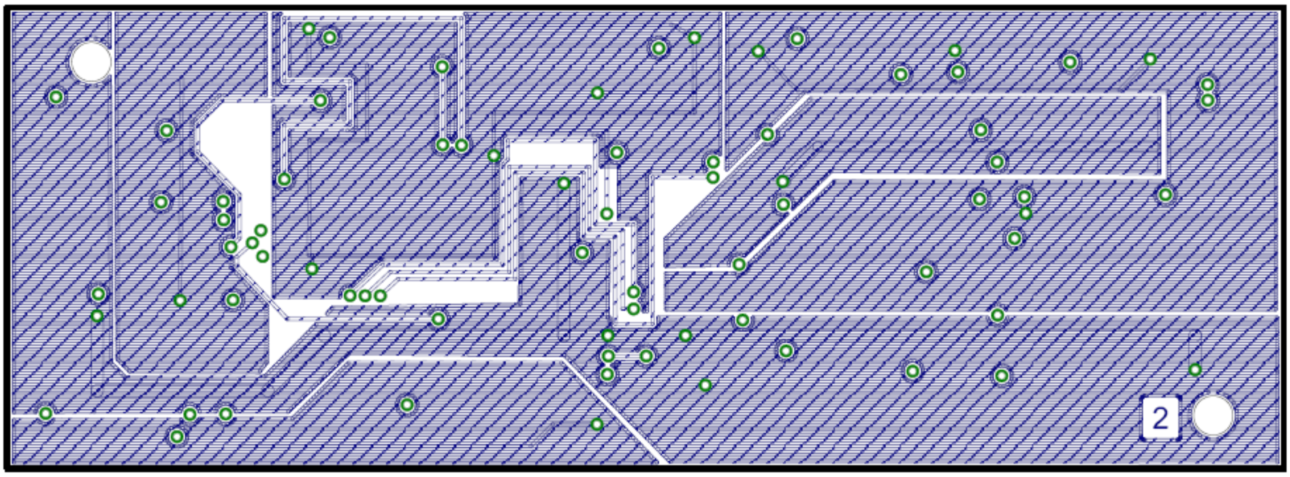
Bottom Screen_printing



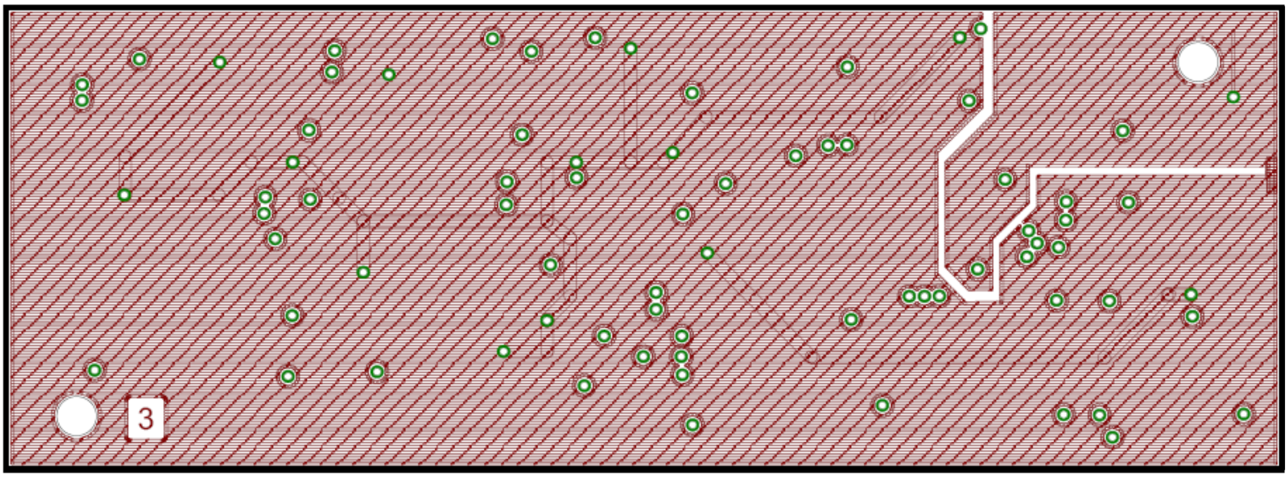
Bottom Screen_printing and Components



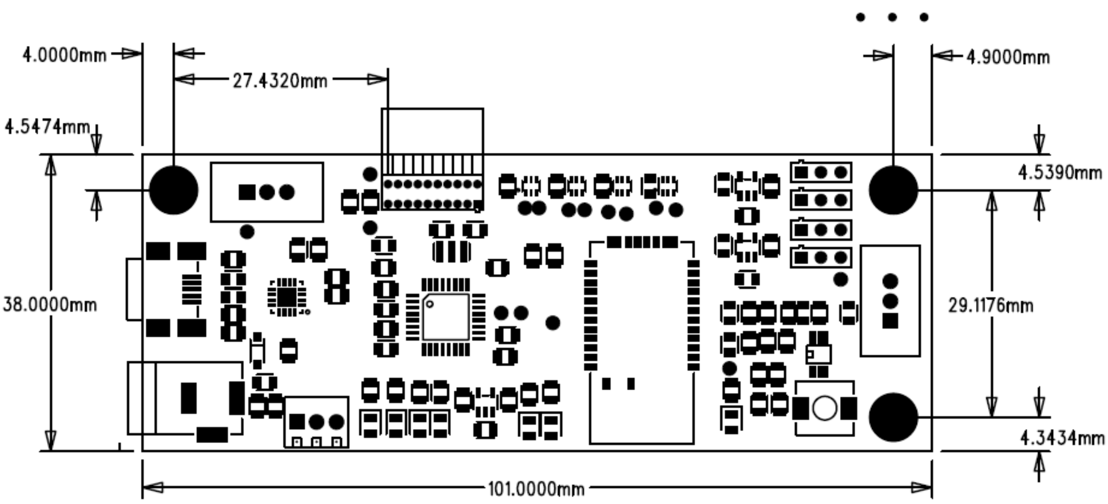
Layer 2 Copper



Layer 3 Copper



Mechanic



Appendix C

Sensors Comparative Tables

The following tables presents a comparative analysis of some sensors. The costs is the unitary costs for a 1000 pieces. These do not pretend to be a comprehensive reference guides, because the related technology is in rapid and continuous mutation (Barbour, 1992).

Gyroscopes

Producer	Model	Nr. axes	Ranges [°/s]	Sensitivity	Output Type	Voltage	Absorbed Current [mA]	Costs [$]
SS (Sensing, 1913)	CRS05 01	1	50	40mV/°/s	An	5	35	x
SS	CRS05 75	1	75	27mV/°/s	An	5	35	x
AD (Analog, 1965)	ADXRS401	1	75	15mV/°/s	2Hz	5	6	22.0
AD	ADIS16080	1	80	0.098°/s/LSB	SPI	5	7	34.95
AD	ADIS16251	1	20-80	0.004°/s/LSB	SPI	5	18	44.95
AD	ADXRS150	1	150	1.5mV/°/s	2Hz	5	6	30.00
SS	CRS05 02	1	200	10 mV/°/s	An	5	35	x
AD	ADXRS300	1	300	5 mV/°/s	2Hz	5	6	30.00
AD	ADIS16100	1	300	0.244°/s/LSB	SPI	5	7	34.95
AD	ADIS16120	1	300	0.2°/s/LSB	An	5	100	629.00
AD	ADIS16250	1	80-320	0.018°/s/LSB	SPI	5	18	41.98
AD	ADIS16255	1	80-320	0.018°/s/LSB	SPI	5	18	55.90
AD	ADIS16350	3	80-320	0.018°/s/LSB	SPI	5	18	x

Accelerometers

Producer	Model	Nr. axes	Ranges [g]	Sensitivity	Output Type	Voltage	Absorbed Current [mA]	Costs [$]
AD	ADXL213	2	1.2	30%/g	PWM	5	0.7	9.70
AD	ADXL103	1	1.7	1000 mV/g	An	5	0.7	7.75

AD	ADIS16003	2	1.7	1.2mg/LSB	SPI	3 - 5.25	1.4	17.75
AD	ADXL204	2	1.7	620 mV/g	An	3.3	0.5	12.00
FS (Freescale, 2010)	MMA7260QT	3	1.5	800 mV/g	An	3.3	0.5	5,67
FS	MMA6280Q	2	1.5	800 mV/g	An	3.3	0.5	5.59
FS	MMA1260D	1(Z)	1.5	1200 mV/g	An	5	2.2	5.68
FS	MMA2260D	1	1.5	1200mV/g	An	5	2.2	5.68
VTI (VTI, 1991)	SCA6xx	1	1.7	1200mV/g	An	5	2	x
VTI	SCA3000 D	3	2	1333 cts/g	SPI-I^2C	2.35 - 3.6	0.48 - 0.65	x
VTI	SCA3100	3	2	900 cts/g	SPI	3.3	3	x
VTI	SCA21xx	2	2	900 cts/g	SPI	3.3	3	x
CL (Colibrys, 2001)	MS8002	1	2	1000mV/g	An	5	1.5	x
CL	MS7002	1	2	500mV/g	An	3	0.7	x
CL	SiFlex 1500S	1	3	1200mV/g	An	6-15	10	x
CL	SiFlex 3000L	3	3	1200mV/g	An	6-15	30	x
MS (Measurement, 1983)	302x 005	1	5	15mV/g	An	5	x	x
MS	305x 005	1	5	3.6mV/g	An	5	1.5	x
MS	302x 200	1	200	0.3mV/g	An	5	x	x
MS	3038 200	1	200	0.22mV/g	An	5	x	x
ST (ST, 2009)	LIS3L06AL	3	2-6	660-220 mV/g	An	3.3	0.95	9.67
ST	LIS3LV02DQ	3	2-6	1024-340 LSB/g	SPI-I2C	3.3	0.6-0.65	9.93
ST	LIS2L02AS4	2	2-6	660-220 mV/g	An	3.3	0.85	6.05
ST	LIS2L02AQ3		2-6	660-220 mV/g	An	3.3	0.85	6.05

Magnetic Sensors

Producer	Model	Nr. axes	Ranges [gs]	Sensitivity [mV/V/gs]	Res [µgs]	Voltage	Absorbed Current [mA]
NXP (NXP, 2006)	KMZ10A1	1	0.625	1.76	x	5	0.7
HM (Hitachi, 1901)	HM55B	2	1.8	1.6	30	3	9
HW (Honeywell, 2002)	HMC6052	2	2	0.5	x	3	5
HW	HMC1001	1	2	3.2	27	5	10
HW	HMC1002	2	2	3.2	27	5	10
NXP	KMZ50	1	2.5	1.28	x	5	0.7
NXP	KMZ51	1	2.5	1.28	x	5	0.7
HW	HMC1021S	1	6	1	85	5	5
HW	HMC1021Z	1	6	1	85	5	5
HW	HMC1021D	1	6	1	85	5	5
HW	HMC1022	2	6	1	85	5	5
HW	HMC1041Z	1	6	1	160	5	1
HW	HMC1042L	2	6	1	160	3	1
HW	HMC1043	3	6	1	120	3	10
HW	HMC1051Z	1	6	1	120	3	10
HW	HMC1051ZL	1	6	1	120	3	10
HW	HMC1052	2	6	1	120	3	10
HW	HMC1052L	2	6	1	120	3	10
HW	HMC1053	3	6	1	120	3	10
HW	HMC1055	3	6	1	120	2.5	1
NXP	KMZ10A	1	6.25	1.28	x	5	0.7
NXP	KMZ10B	1	25	0.32	x	5	0.7
NXP	KMZ11B1	1	25	0.32	x	5	0.7
NXP	KMZ10C	1	93.75	0.12	x	5	0.7

Appendix D

Design of a possible Band 1 SOPM – Implementation Detail

The features exposed in Chapter 4 have made the choice to fall on the battery of Varta Easy Pack 2000 (Ariani, 2006) (Fig. D. 1). The principal characteristics of the battery are reported in Table D. 1.

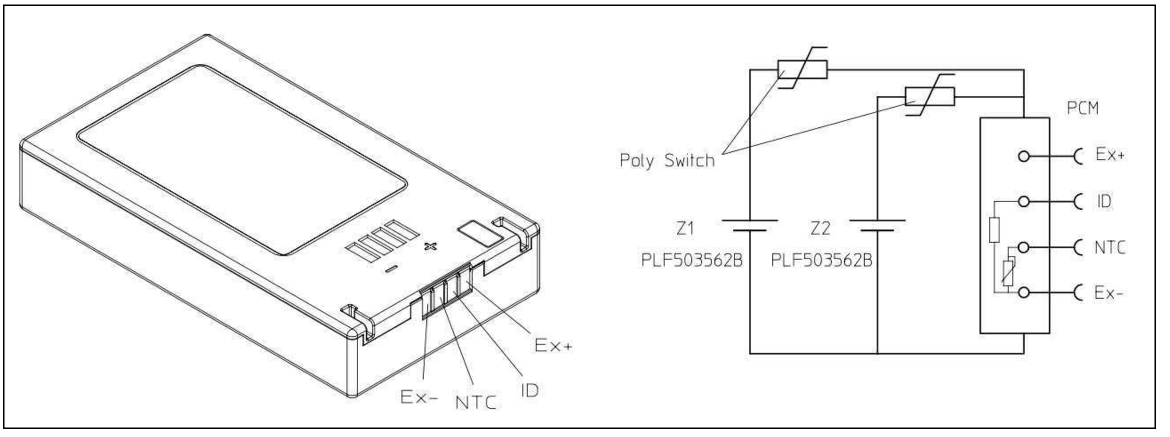


Fig. D. 1 Varta Easy Pack 2000

Nominal Voltage	3,7 V
Voltage Range	[4.2V - 2.75] V
Nominal Capacity	2200mAh
Maximum Discharge current	2 A
Over – Current protection (automatic disconnection)	3, 2A
Under – Voltage protection (automatic disconnection)	2, 365 V
Over – Voltage protection (automatic disconnection)	4,32 V
Internal temperature check	yes

Table D. 1

Before proceeding to the description of the battery charger, it is important focus on the charging cycle of the battery. This is illustrated in Fig. D. 2 and is represented by a constant current - constant voltage cycle: in the first phase, until the battery voltage is lower than 4, 2V, the battery must be recharged with a constant current value of 550mA; reached the threshold voltage, the current must be kept constant. After 7 hours, or reached a current consumption of less than 44mA, the charge is finished.

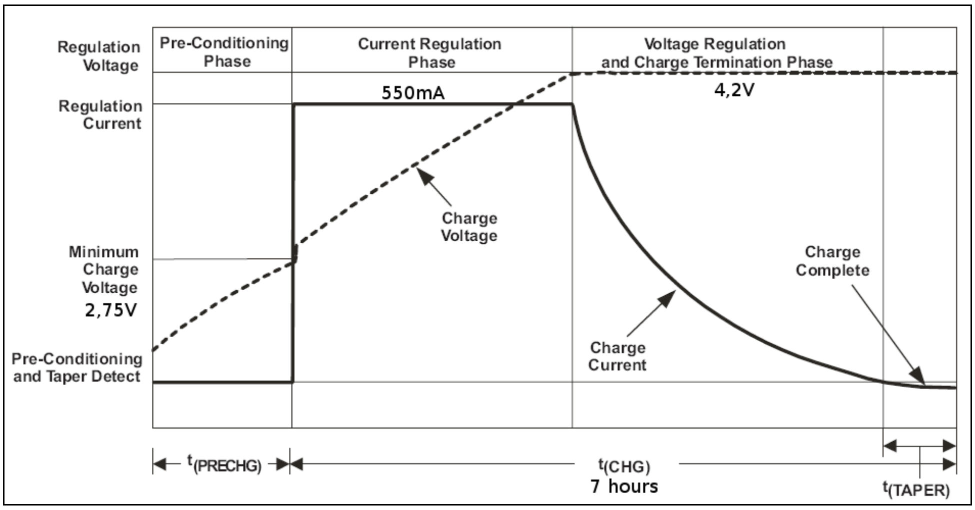


Fig. D. 2 Charging cycle

After having chosen the style of battery, the design space for the voltage regulator starts becoming bounded. In the case of a Lithium polymer battery, with the characteristics described above, there are still a myriad of different options. There are different possibilities, but is given only the choice made based on the specification.

The choice fell on the switching regulators: these regulates voltage by switching a power transistor between saturation and cut off with a variable duty cycle to achieve the correct average voltage output. This kind of design is efficient, allows a wider range of input voltages and differing system topologies. However, these advantages come at a cost of complexity and price. Switching regulators exist in many different forms, however, in the case of this design we are interested in DC/DC style converters of the buck/boost topology.

A boost converter is a design with a DC output which is greater than it's DC input while a buck converter is a design with a DC output which is lower than it's DC input. When looking at the design specifications, the battery's useful range passes through the required V_{out}. This implies that a combination buck/boost design would allow to utilize the battery to it's fullest extent, *i.e.*

$V_{out} > 3.6$ the regulator is in buck mode

$V_{out} <= 3.6$ the regulator is in boost mode

After recognizing that the SOPM design would benefit from a combined buck/boost topology, the choice of which switching regulator to use must be made. In the case of this particular design, we decided to narrow our choices to the LTC 3530 (Linear, 2007). The efficiency (Fig. D. 3) is quite high for the battery voltage range and the output current needs.

When designing a power supply of this sort, a number of components must be selected in addition to the primary controller IC. Fig. D. 4 shows the final design of the LTC 3530. The various choices will be explained below:

- R2 and R3 determine the output voltage:

$$V_{out} = 1.215 * (1+ \frac{R2}{R3})$$

The values for R2 and R3 were chosen based on available resistor values. First the voltage was selected by choosing a ratio of R2 to R3 to be equal to 2 so:

$$V_{out} = 1.215 * (1+2)= 3.645V_{out}$$

Then actual off the shelf resistor values were chosen to be 1MOhm and 500kOhm.

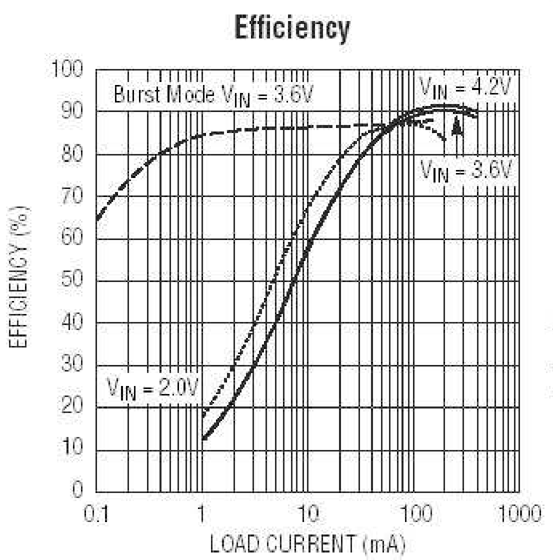


Fig. D. 3 Switching regulator efficiency

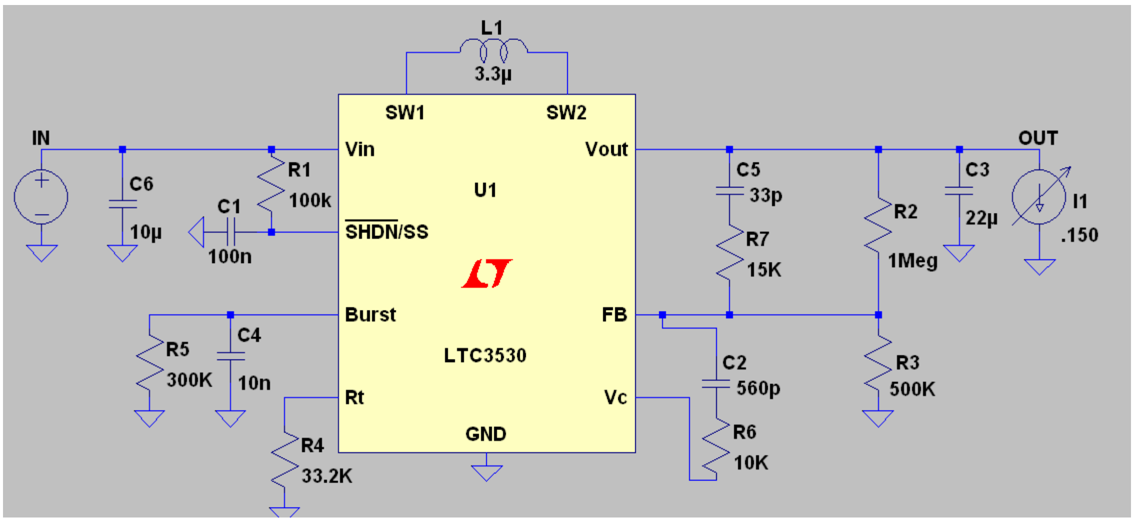


Fig. D. 4 Switching regulator design

- L1 is the inductor and is chosen by combining the switching frequency, the maximum allowable ripple current, the minimum input voltage, the maximum input voltage, the output voltage, and the maximum output load current with the formulas:

  $L_{Boost} > (V_{in(min)} * (V_{out} - V_{in\ min}))/(f*\Delta I_L*V_{out})$ 2.9 uH

  $L_{Buck} > (V_{out} * (V_{in\ max} - V_{out}))/(f*\Delta I_L*V_{in\ max})$

  which state that the inductor must be greater than 2.9µH for L_{Boost} and and 2.8µH for L_{Buck} to achieve a ΔI_L of about 214 mA. This implies that the inductor must have a value larger than 2.9µH, so it was chosen the closest value available of 3.3µH.

- C3 is the output capacitor and is chosen by the following formulas:

  $C_{Boost} > (I_{out\ max} * (V_{out} - V_{in\ min}) * 100)/(\%RippleBoost*V_{out}^2 * f)$

  $C_{Buck} = ((V_{in\ max} - V_{out})*100) /(8*L*f^2*V_{in\ max}*\%RippleBuck)$

  which states that the capacitor value larger than 2.7 uF for C_{Buck} and 21.6 uF for C_{Boost} in order to achieve a boost ripple of 10% and a buck ripple of 0.2%.

- C1 and R1 define the Soft - Start rate, for the powers on. To determine these values, the following approximation is used:

  t = RC = 100nF*100kOhm = 0.01s

  so in 10 ms the capacitor should have a voltage of 0.66*4.2 = 2.77V where 0.66 implies that in 1 time constant the capacitor is at 2/3 of it's total voltage. So 2.77V/10ms = 0.277 V/mS ramp up rate. So, 1V should be reached in about 3.6 mS.

- R4 is used to set the oscillator frequency which is a parameter which must be known in order to determine what size of an inductor we will need later. This is determined with the equation given in the data sheet:

  $f_{khz} = 33170/R_T = = 33170/33.2 = 1$ MHz

  where R_T should be expressed in kOhms

- R5 and C4 are used to determine when the device enters and exits "burst mode". Burst mode is used to minimize the quiscent current of the SMPS at light loads and improve the overall efficiency. We chose to set the burst mode current limits at the following:

  Enter Burst Mode: $I = 8.8/R_{Burst\ (in\ kOhm)} = 8.8/300 = 29.3$ mA

  Exit Burst Mode: $I = 11.2/R_{Burst\ (in\ kOhm)} = 11.2/300 = 37.3$ mA

- C4 is chosen using the following equation:

  $C_4 >= Cout*Vout/60,000$

With the above design, Fig. D. 6 shows a number of simulations varying the input voltage from 4.2V to 2.8V.

The simulated efficiency with this design is:

Voltage Input	Efficiency (%)
2.8	94.7
3.8	95.3
4.2	95.6

Fig. D. 5

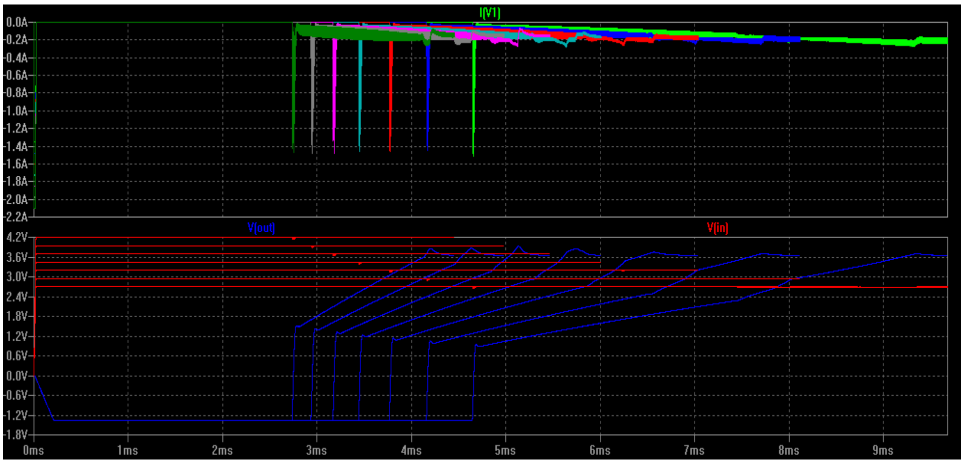


Fig. D. 6 Efficiency Simulation results

Fig. D. 7 shows that our output ripple is about 2 to 3 mV at its peak (this snapshot was taken at the most unstable point in the voltage output).

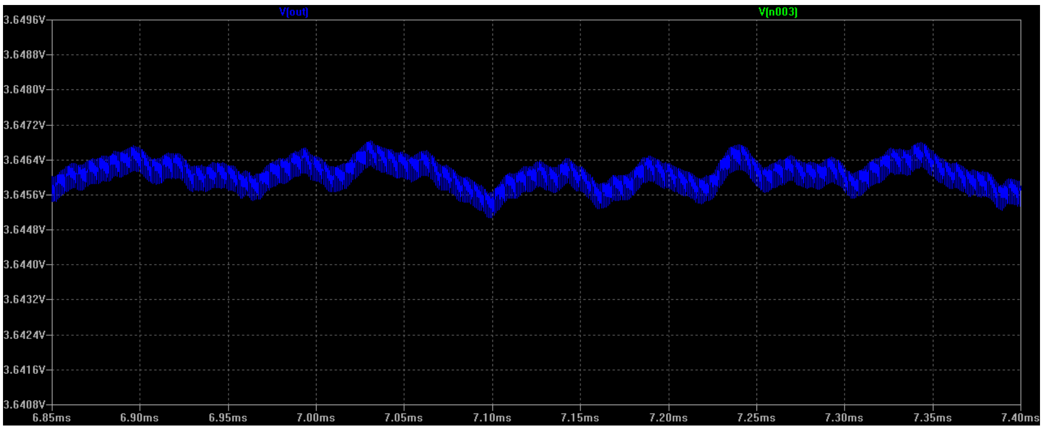


Fig. D. 7 Simulated Ripple results

The actual realization of the switching regulator is analyzed below. To begin in Fig. D. 8 is reported the ripple of the regulator output voltage. This is around the 280mV peak – peak. Fig. D. 9 shows the soft – start functionality. The power on time is around 100 μsec using a load of 180mA.

The last component of the modules is the battery charger. As seen, in general the battery charger is selected based on the charging/discharging cycle characteristics and on other two design choice:

- the need to powering the load during the battery charging;
- the charging interface availability.

Regarding the Smart Objects design, allow the use of the entire system during the charging of the battery, could be an added feature. In addition, the charging only through a USB port may be limited for users accustomed to the use of computers.

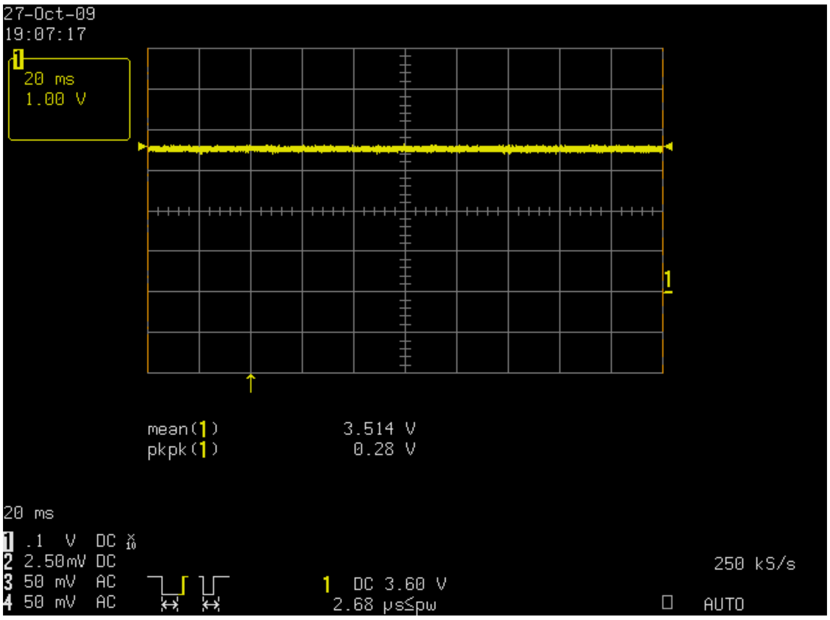


Fig. D. 8 Regulator Output voltage ripple

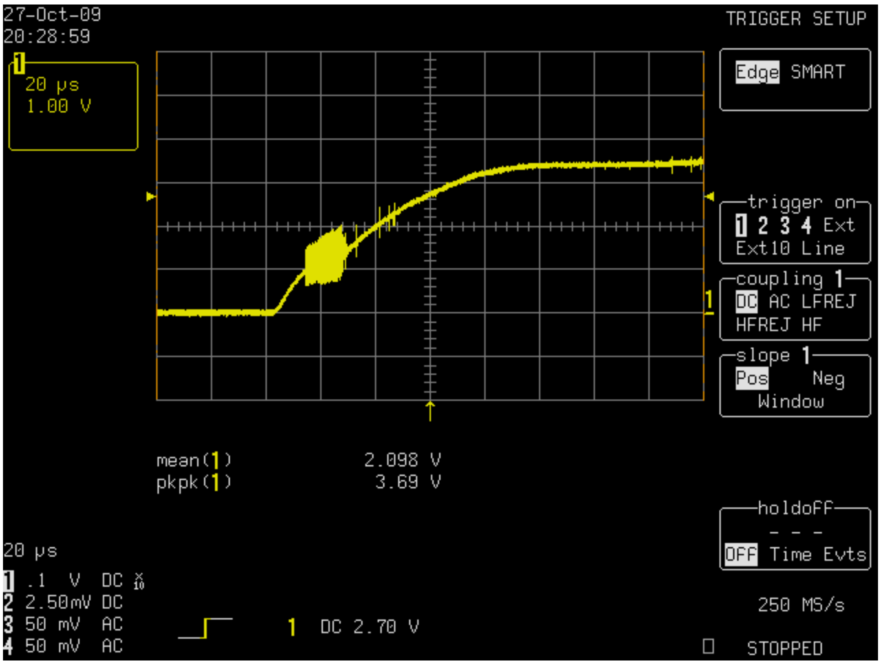


Fig. D. 9 Soft–start functionality

The latter is was solved by choosing a solution that enables the charging or through a USB port or through a wall transformer.

The former is was solved choosing the Power Path® technology, which allow to manage various power sources and various loads while allowing to load the battery during normal functioning of the load. A simple and versatile solution to the requirements described above is the circuit LTC4055 (Linear, 2008), which a typical application is shown in Fig. D. 9.

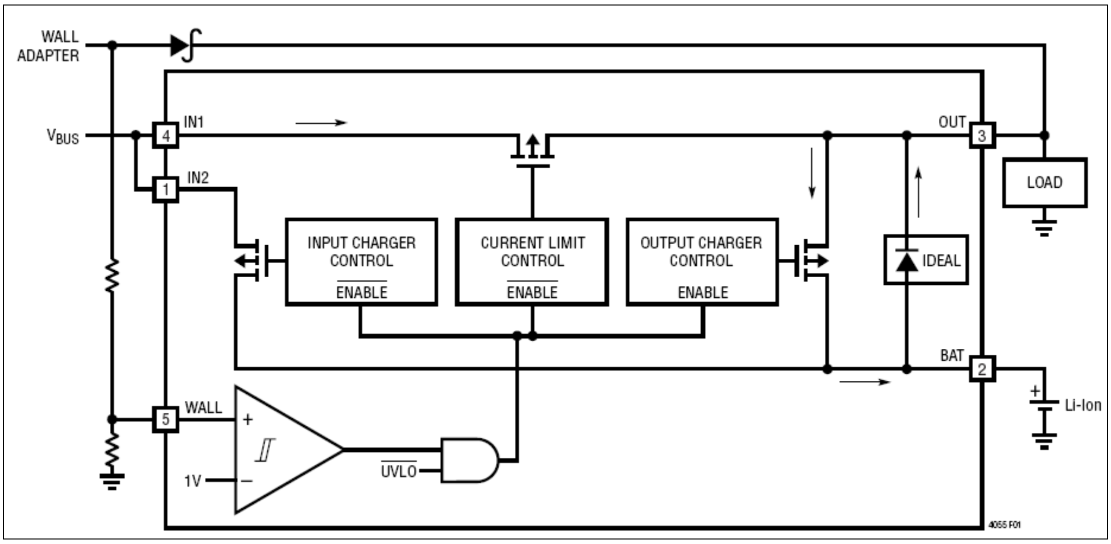


Fig. D. 10 LTC4055 block diagram

The LTC4055 is basically designed for charging a lithium battery through USB power, and it has been provided to an external supply voltage of 5V. Fig. D. 11 shows the final design of the LTC4055.

The various choices will be explained below:

- Current limitation: the maximum current have to be less than 500mA (in the case of USB supply). This value is imposed by the R_{CLPROG} resistor:

$$R_{CLPROG} = \frac{49000}{I_{CLPROG}} = \frac{49000}{0,5} = 98\ K\Omega$$

The actual choice is $R_{CLPROG} = 100\ K\Omega$

- Charging Current: This value is imposed by the R_{PROG} resistor:

$$R_{PROG} = \frac{49000}{I_{CHG}} = \frac{49000}{0,55} = 88\ K\Omega$$

- Charging period: the battery charging period is 7 hours. This is imposed by C_{Timer}:

$$C_{Timer} = \frac{t_{TIMER} * 10^{-2}}{3 * R_{PROG}} = \frac{7 * 10^{-2}}{3 * 8800} = 265\ nF$$

- Regarding the temperature protection, the above components imposes the temperature operating range of:
  T_{hot} = 323 °K =50 °C
  T_{cold} =273 °K = 0 °C
  equivalent to the smart – battery range.

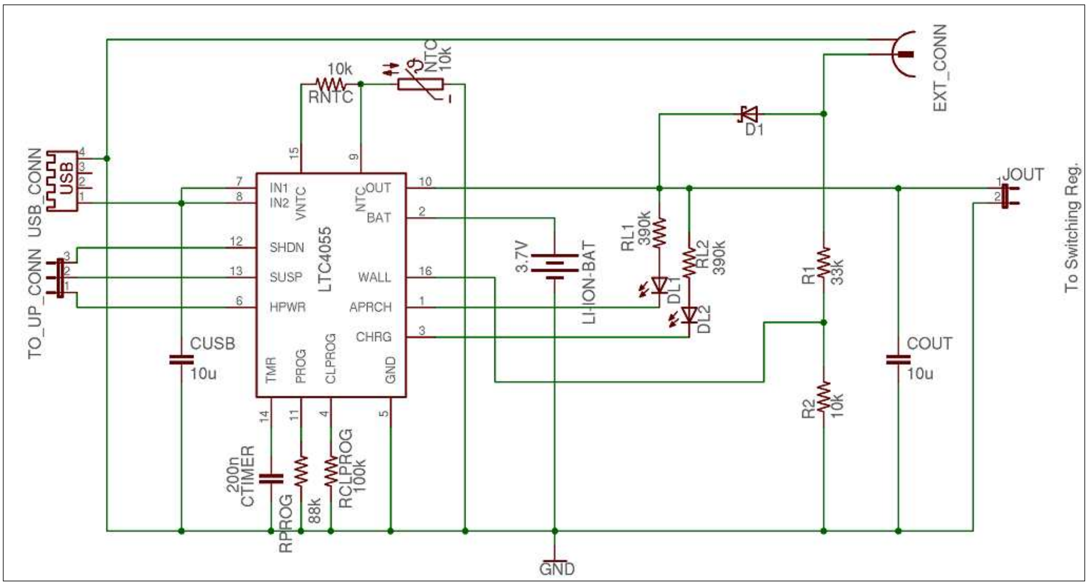
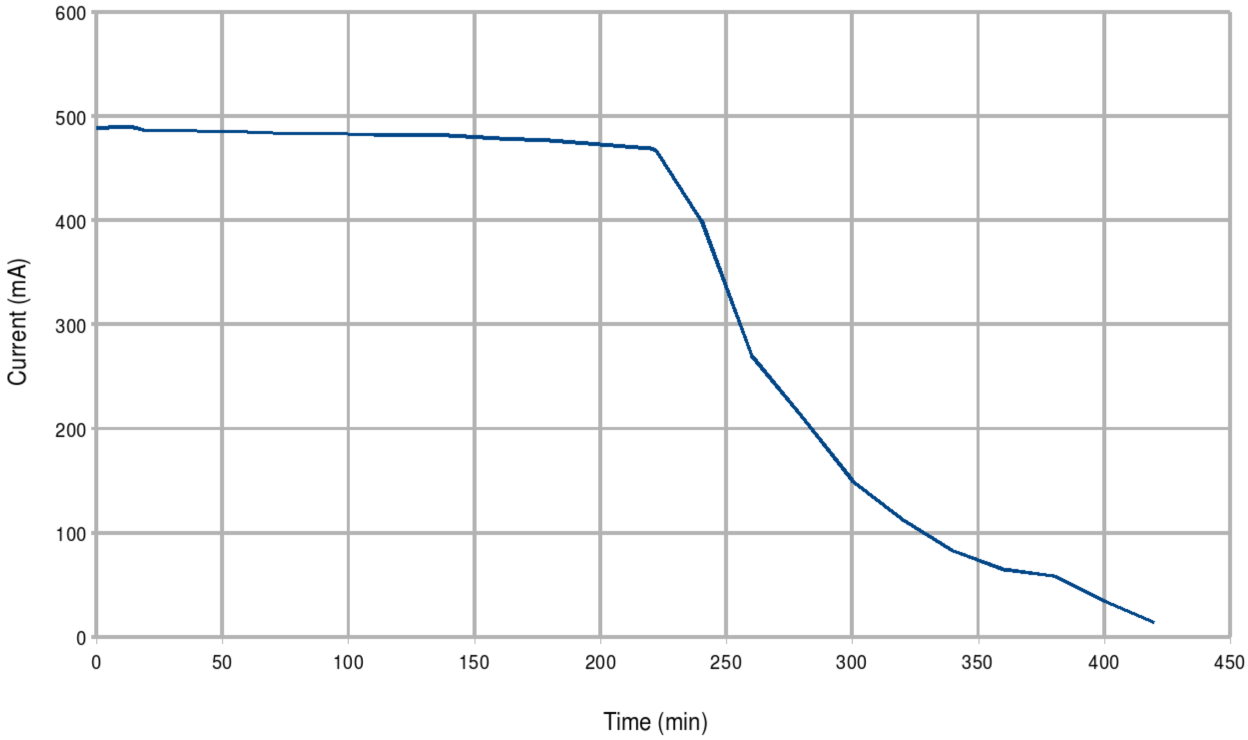


Fig. D. 11 Battery charger design

Concerning the results, Fig. D. 12 shows voltage and current of an entire battery charging cycle utilizing a wall transformer. Fig. D. 13 shows the slope of the voltage and the current during a battery charging partial cycle utilizing a wall transformer: despite having already reached the threshold voltage (4, 2V), the charge continues until the expiration of the timer (3 hours in this case).

Fig. D. 14 shows the battery current variation varying the current drawn by the load. The variation occur because the absorption by the USB bus must not exceed the value set (in this case 1000mA).

Concerning the entire system, Fig. D. 15 shows the efficiency shows the performance as a function of load current for four input voltage: 5 V, 4,2V, 3,7 V e 2,5 V. The former represents the voltage input when the system is charging the battery utilizing a wall transformer. In the typical operation condition (load current from 80m to 100mA and input voltage of 3,7V) the efficiency varies from 80% to 84%.



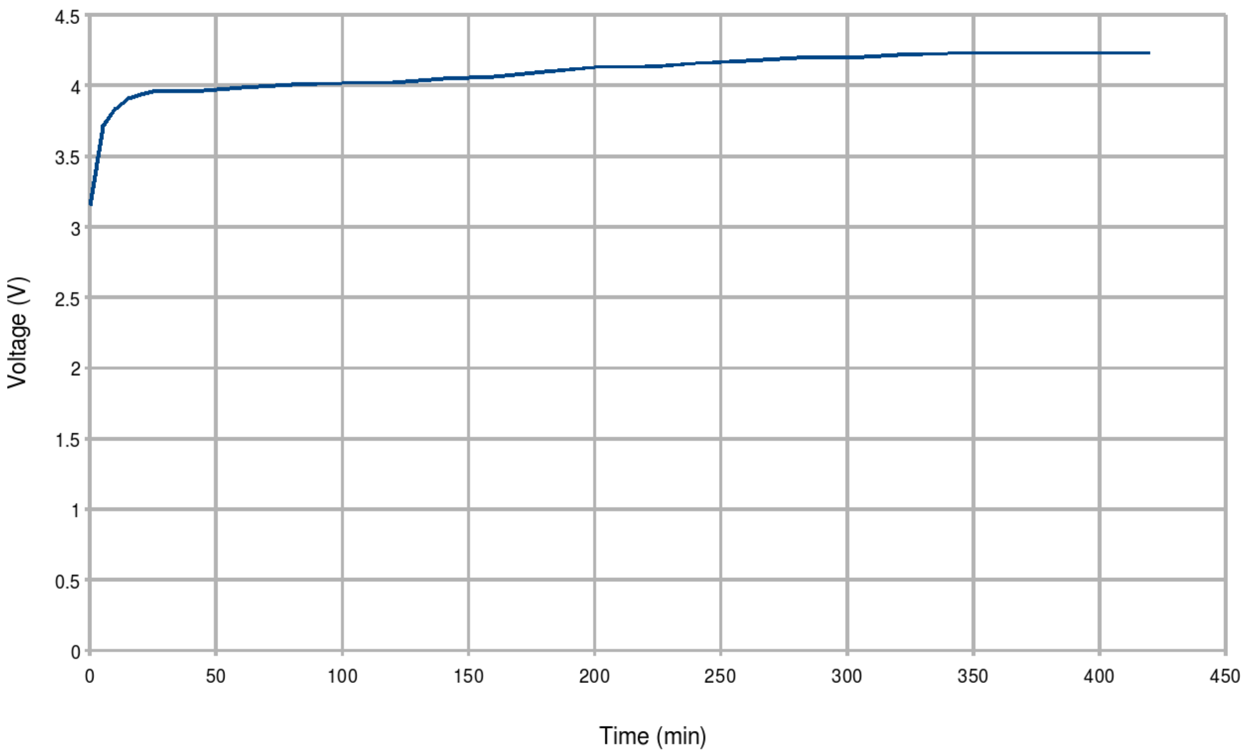


Fig. D. 12 Battery charging cycle utilizing a wall transformer

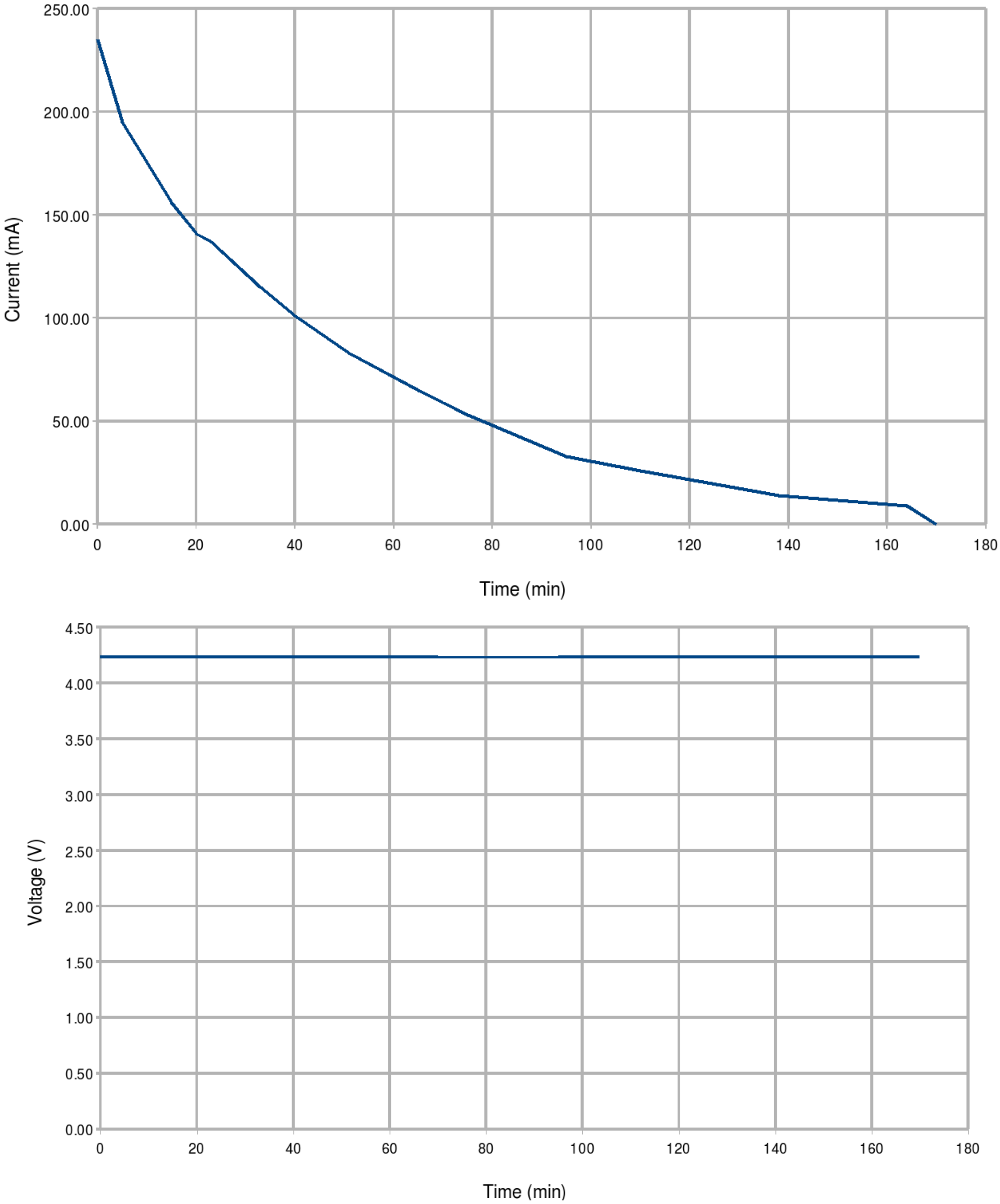


Fig. D. 13 Partial Battery charging cycle

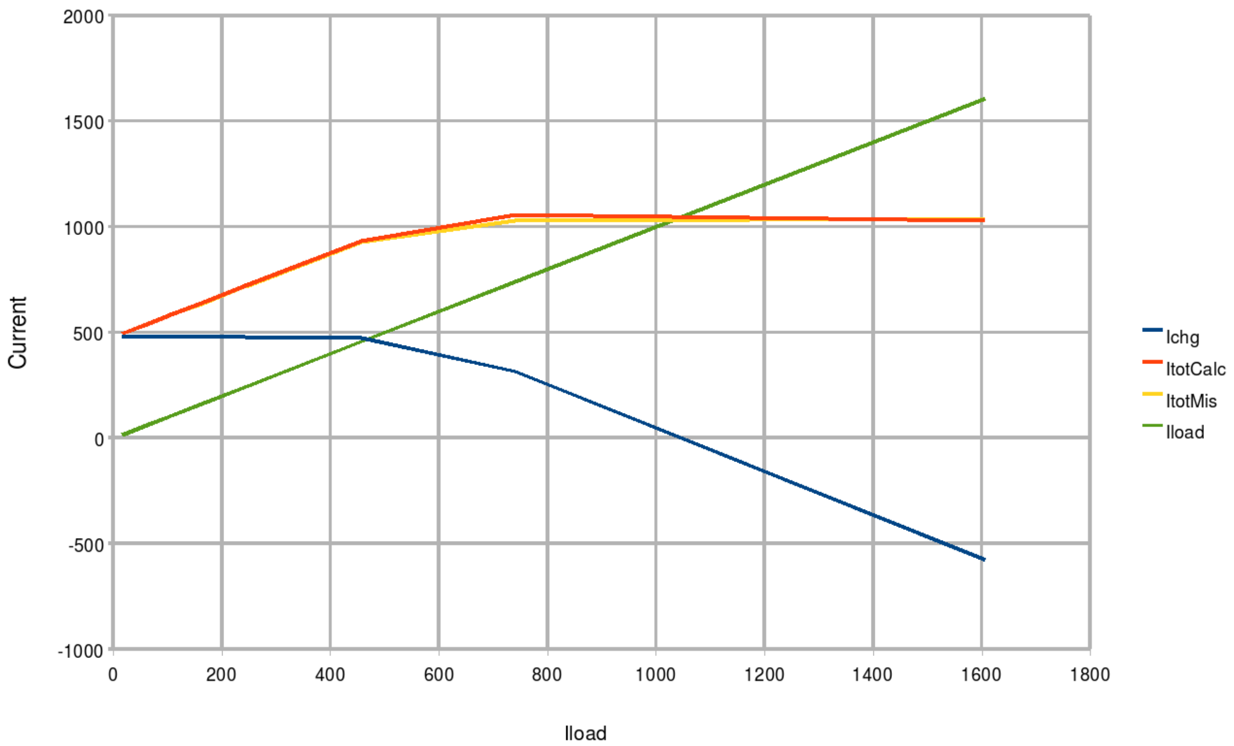


Fig. D. 14Charging current vs. Load current

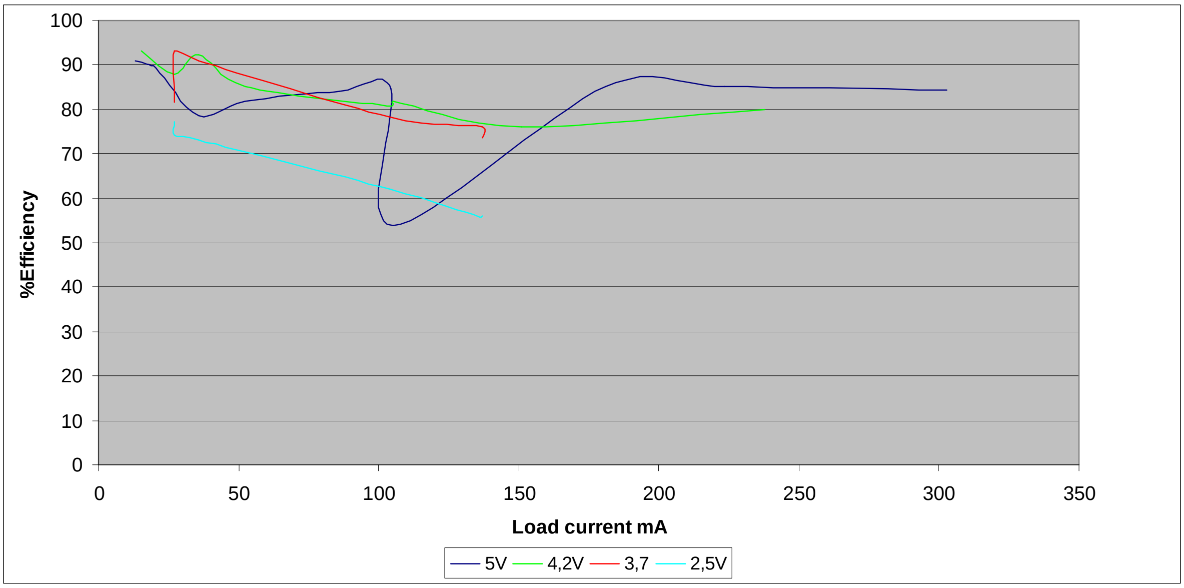


Fig. D. 15 System Efficiency vs Load Current

Appendix E

Fixed - Point Arithmetic and Trigonometric Evaluation

The microprocessor studied for this doctoral work is a 12 bit fixed-point. The problems with this (and also with less precision microprocessor) is the loss of precision caused by the absence of decimals and the fact that the software is supposed to support different data characterized by different sensor ranges. This can be achieved for each sensor:

- By spreading the sensor range on the whole ADC range (searching the maximum and minimum value and calculation offset and scale factor,
- Using known multiplier scale value for each sensor

In this way all the range of sensors start at zero and there is not loss of precision.

Performing floating point operation is the next step (Gordon, 2010).

The multiplication for a floating point value must be integer input and output value. The solution are two integer operations: a multiplication followed by a division. In fact if the operation is:

$$C = A * 0.3456 \qquad \textbf{Eq. E. 1}$$

we can see the number 0.3456 like 3456/10000 (=M/D, where M=3456 and D= 10000). Now the operation can be seen as two integer operations:

$$C = \frac{A * 3456}{10000} \qquad \textbf{Eq. E. 2}$$

Integer division will produce an integer results. So, if the results have a fractional part, the division will truncate the result. It is often necessary that the division round to the nearest integer. Adding 0.5 before the division, help in this task. Now the calculation is the following:

$$\mathbf{C} = \frac{(A * 3456) + 5000}{10000} \qquad \textbf{Eq. E. 3}$$

This trick can be applied whenever an integer division need to be performed. In fact the calculation of the division between A and B can be calculate as:

$$C = \frac{A}{B} = \frac{A + \frac{B}{2}}{B} \qquad \textbf{Eq. E. 4}$$

The numerical computation of complex functions (also trigonometric) is necessary to the tracking application. In the next pages will be shown how they were implemented and how they work.

- Square Root: the square root function is computed by means of a Look-Up-Table which is, in this case, a 1002 buffer of element. Each element is the equivalent of the real square root multiplied for a multiplier scale value which depend on the approximation of these number. Fig. E. 1 shows the trend of the output of the numerical function, on an input range from 0 to 978, with a step of 2. As shown in Fig. E. 2 the trend of the real square root (on the same input range) is equivalent. In this case it in not advantageous indicate in a graph the difference between the real and the computed square root due the multiplier scale value.

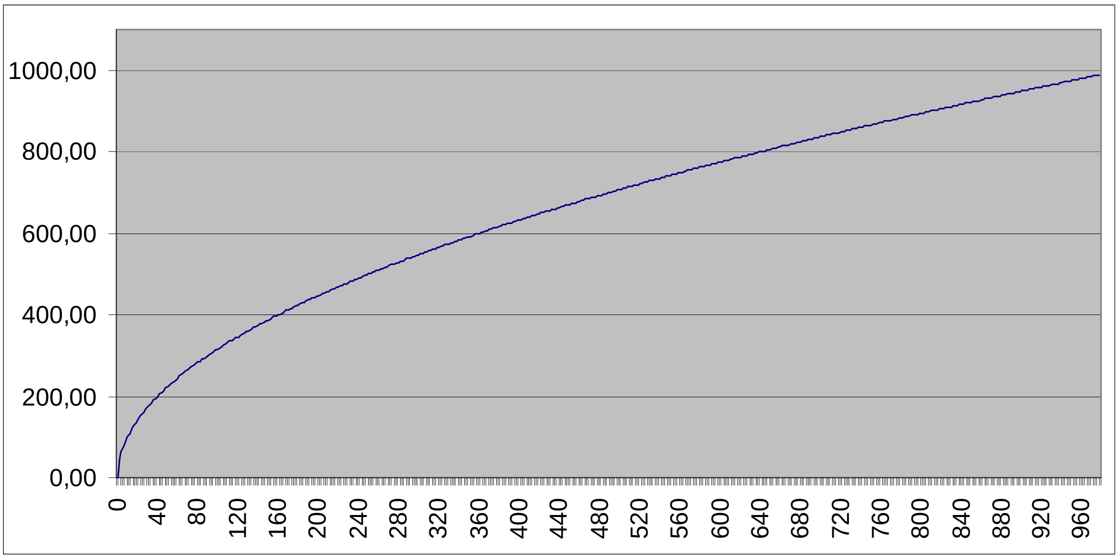


Fig. E. 1 Numerical Square- Root Plotting

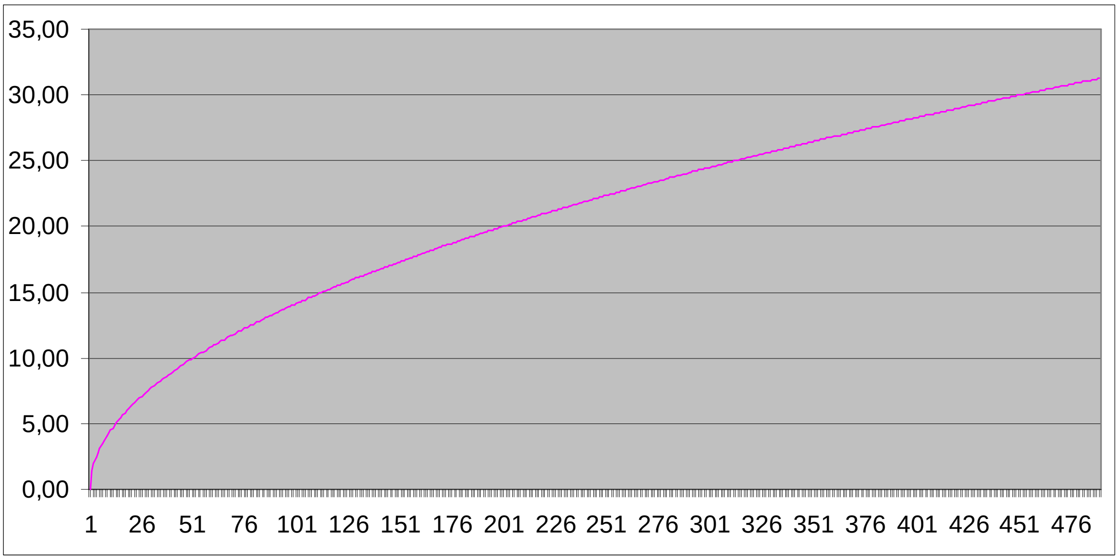


Fig. E. 2 Real Square- Root Plotting

- Fourth Root: the fourth root function is computed by means of a Look-Up-Table which is, as in the case of square root, a 1002 buffer of element. Each element is the equivalent of the real fourth root multiplied for a multiplier scale value which depend on the approximation of these number. Fig. E. 3 shows the trend of the output of the numerical function, on an input range from 0 to 978, with a step of 2. As shown in Fig. E. 4 the trend of the real fourth root (on the same input range) is equivalent. In this case it in not advantageous indicate in a graph the difference between the real and the computed fourth root due the multiplier scale value.

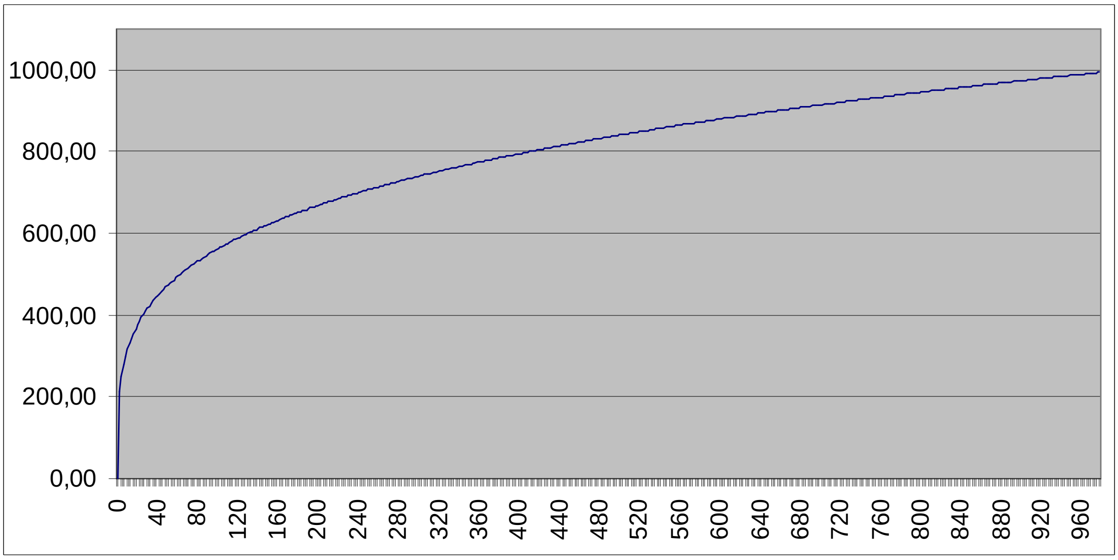


Fig. E. 3 Numerical Fourth- Root Plotting

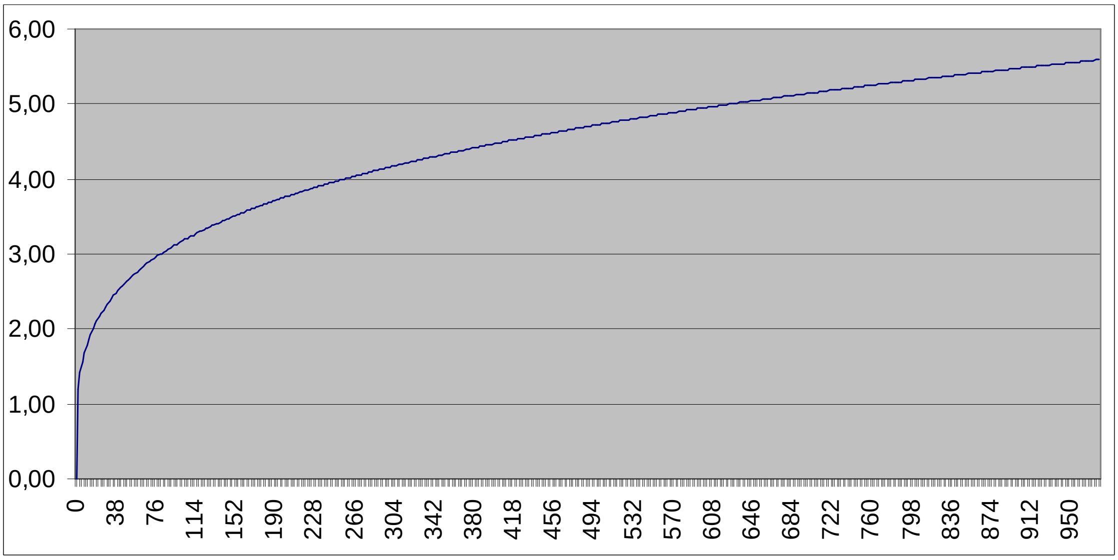


Fig. E. 4 Real Fourth- Root Plotting

- Sine: also the sine function is computed by means of a Look-Up-Table which is, a 1002 buffer of element. Each element is the equivalent of the real sine multiplied for a 1000 multiplier scale value. Fig. E. 5 shows the trend of the output of the numerical function, on an input range from 0° to 359°, with a step of 1°. In this case it is important to compare the error from the computed and the real sine function. As it shown in Fig. E. 6 the maximum error is 0.0022 corresponding to an interval of angle values centred on 0°, 180° and 360°. The minimum error is 0.0001 corresponding to an interval of angle values centred on 90°and 270°. The values for the computed sine function with angles of 0°, 90°, 180°, 270° and 360° are exact.

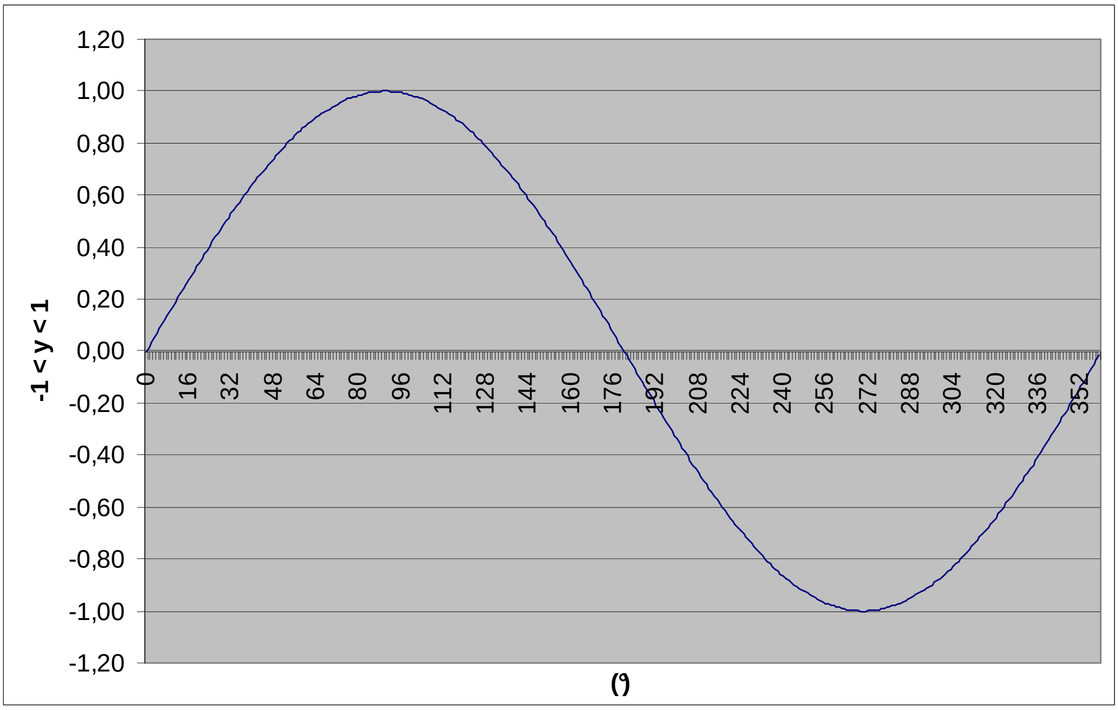


Fig. E. 5 Numerical Sine Plotting

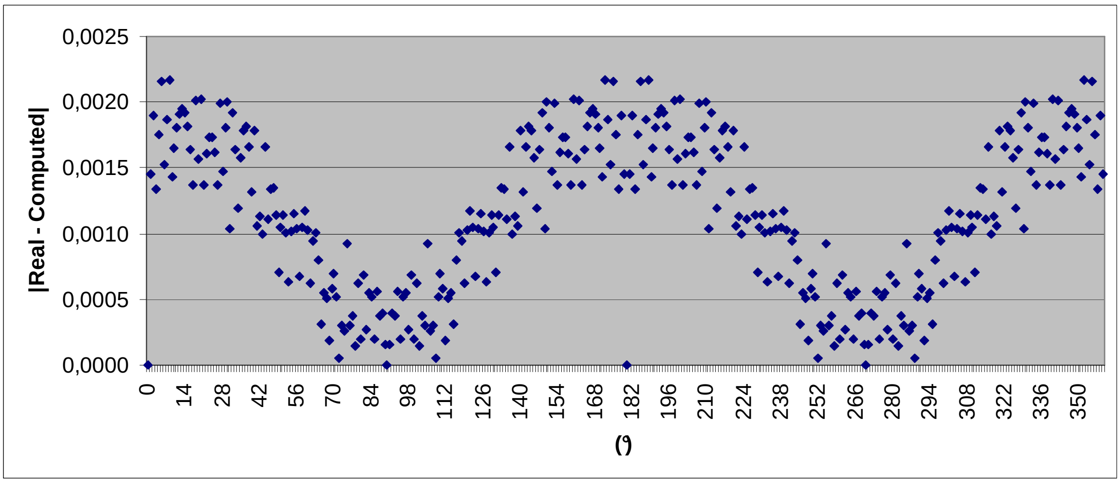


Fig. E. 6 Error between the real and the computed sine function

- Cosine: also the cosine function is computed by means of a Look-Up-Table which is a 902 buffer of element. Each element is the equivalent of the real cosine multiplied for a 1000 multiplier scale value. Fig. E. 7 shows the trend of the output of the numerical function, on an input range from 0° to 359°, with a step of 1°. In this case it is important to compare the error from the computed and the real sine function. As it shown in Fig. E. 8 the maximum error is 0.00217 corresponding to an interval of angle values centred on 90° and 270°. The minimum error is 0.00069 corresponding to an interval of angle values centred on 0° and 180°. The values for the computed sine function with angles of 0°, 90°, 180°, 270° and 360° are exact.

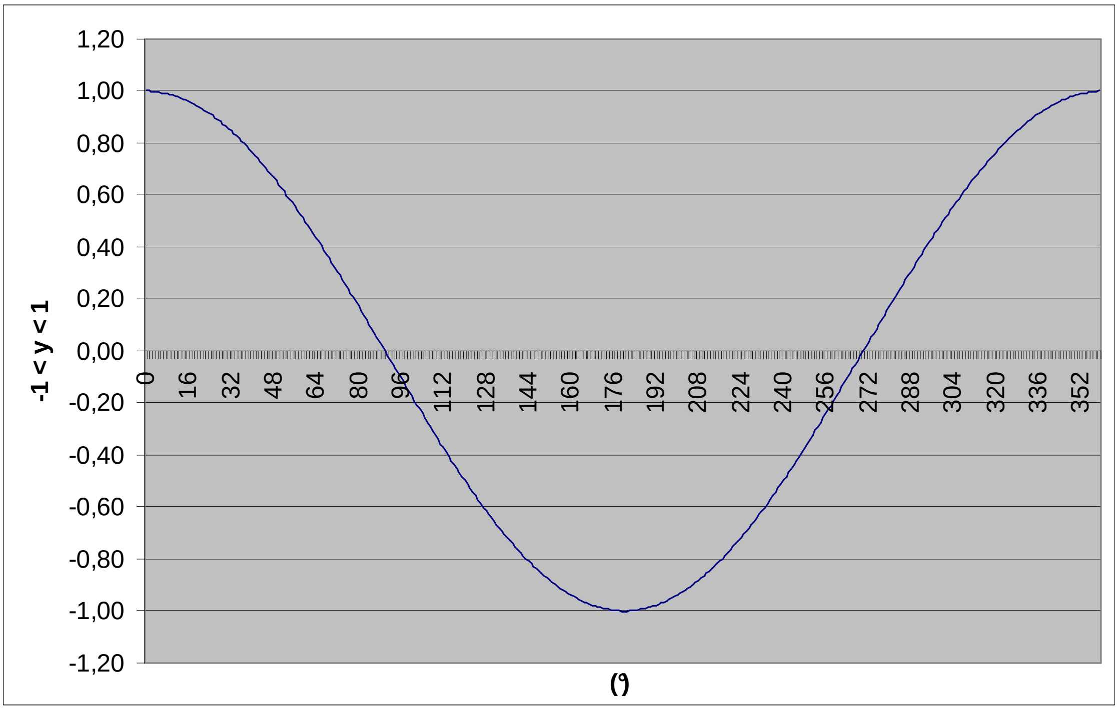


Fig. E. 7 Numerical Cosine Plotting

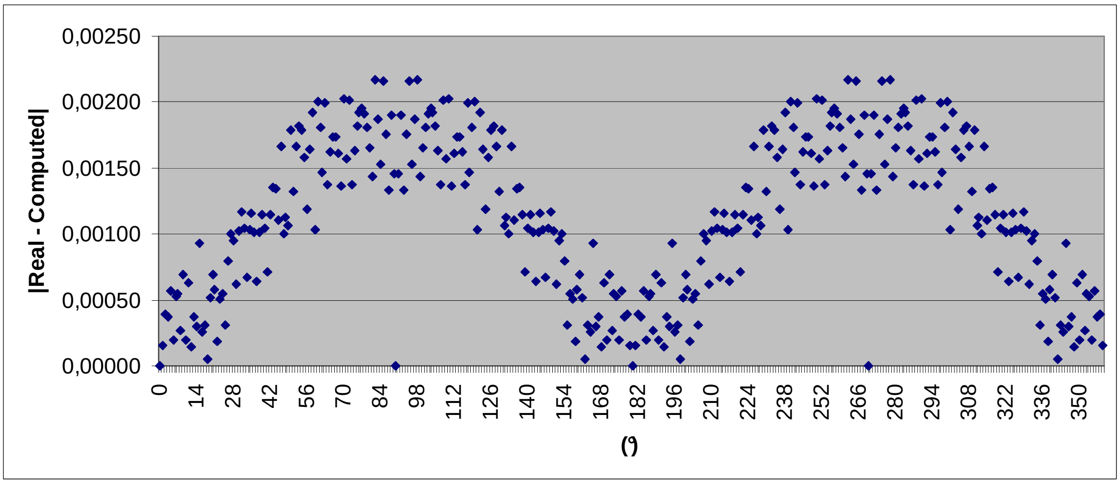


Fig. E. 8 Error between the real and the computed cosine function

- Arctangent: the Arctangent function has been implemented using an iterative method including a set of shift-add based on a selected criterion. This method is called CORDIC (Volder, 1959) and it is used to calculate trigonometric, hyperbolic and logarithmic functions. An overview of this method, and its implementation as numerical is shown in (Andraka, 1998).

Briefly, the method is based on the rotation of vectors (Fig. E. 9) in space, represented by the formulas:

$$X2 = X1\cos(\theta) - Y1 sen(\theta)$$
$$Y2 = Y1\cos(\theta) + X1 sen(\theta)$$

Eq. E. 5

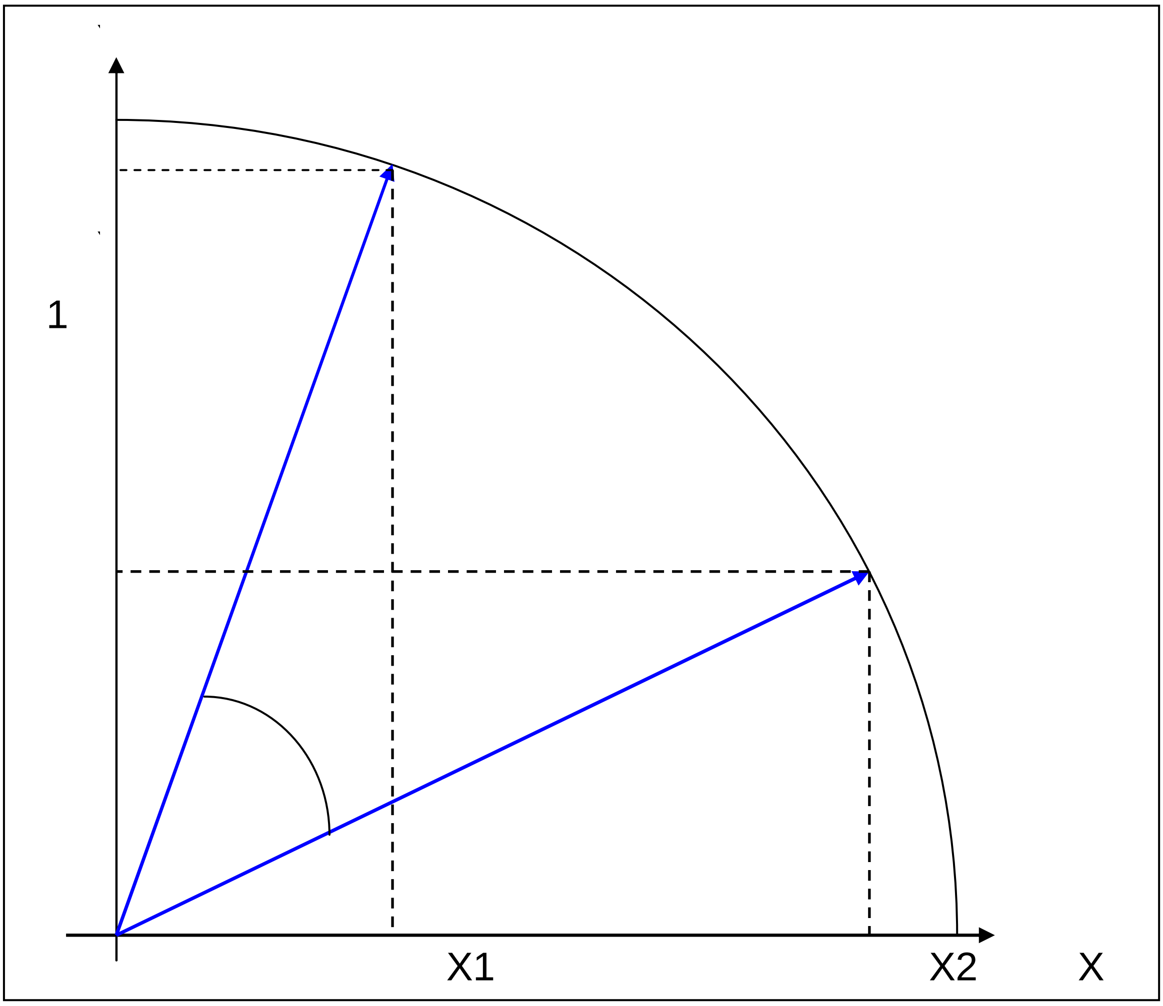


Fig. E. 9 Vector Rotation in Space

It is obtained by dividing the Eq. E.5 by cos(θ):

$$X2 = \cos(\theta)[X1 - Y1\tan(\theta)]$$
$$Y2 = \cos(\theta)[Y1 + X1\tan(\theta)]$$

Eq. E. 6

If the rotations are restricted so that Tan(θ)= $\pm 2^{-1}$, the multiplication by the tangent is reduced to a set of shift operations. For arbitrary angles, the computation is made dividing the rotation angle in a series of successively smaller angles. For each iteration *i*, the decision is in which direction to rotate. The iterative rotation can be expressed as:

$$X_{i+1} = K_i[X_i - Y_i d_i 2^{-i}]$$
$$Y_{i+1} = K_i[Y_i + X_i d_i 2^{-i}]$$
Eq. E. 7

where:

$$K_i = \cos(\arctan 2^{-i}) = \frac{1}{\sqrt{1+2^{-2i}}}$$
$$d_i = \pm 1$$

The angle of a composite rotation is defined by the directions of elementary rotations, which could be represented by a decision table. In the case of this work, the decision table correspond to a Look-Up-Table containing 14 values of

$$\arctan \frac{1}{2^{-i}}$$
Eq. E. 8

multiplied for a multiplicative factor of 100: {4500, 2657, 1404, 713, 358, 179, 90, 45, 22, 11, 6, 3, 1}. To know the value of the final rotation at the equations in Eq. E.7 must need the following:

$$Z_{i+1} = Z_i - d_i \arctan(2^{-i})$$
Eq. E. 9

The CORDIC rotation is generally done in two ways:

1) the Volder rotation which rotates the input vector by a specified angle to diminish the magnitude of the residual angle. The rotation decision at each iteration is based on the sign of the residual angle. For each iteration the equations to be performed are:

$$X_{i+1} = X_i - Y_i d_i 2^{-i}$$
$$Y_{i+1} = Y_i + X_i d_i 2^{-i}$$
$$Z_{i+1} = Z_i - d_i \arctan(2^{-i})$$
Eq. E. 10

where:

$$d_i = sign(Z_i) * 1$$

2) the vectoring mode, in which the vector is rotated by an angle to align with the x-axis. For each iteration the equations to be performed are:

$$X_{i+1} = X_i - Y_i d_i 2^{-i}$$
$$Y_{i+1} = Y_i + X_i d_i 2^{-i}$$
$$Z_{i+1} = Z_i - d_i \arctan(2^{-i})$$
Eq. E. 11

where:

$$d_i = sign(Z_i) * 1$$

Using the CORDIC in vectoring mode, the Arctangent of the ratio of two parameters (as used in this work), can be computed directly, giving the two parameters as inputs and as initial condition $X_0 = 0$. Fig. E. 10 shows the trend of the output of the numerical function, on an input range from -10 to 10. The comparison between the real arctangent function and the computed one is shown in Fig. E. 11: the maximum error is 0.0194 corresponding to -0.40. The corresponding values for angles of 0°, 90°, 180° and 270° are exact.

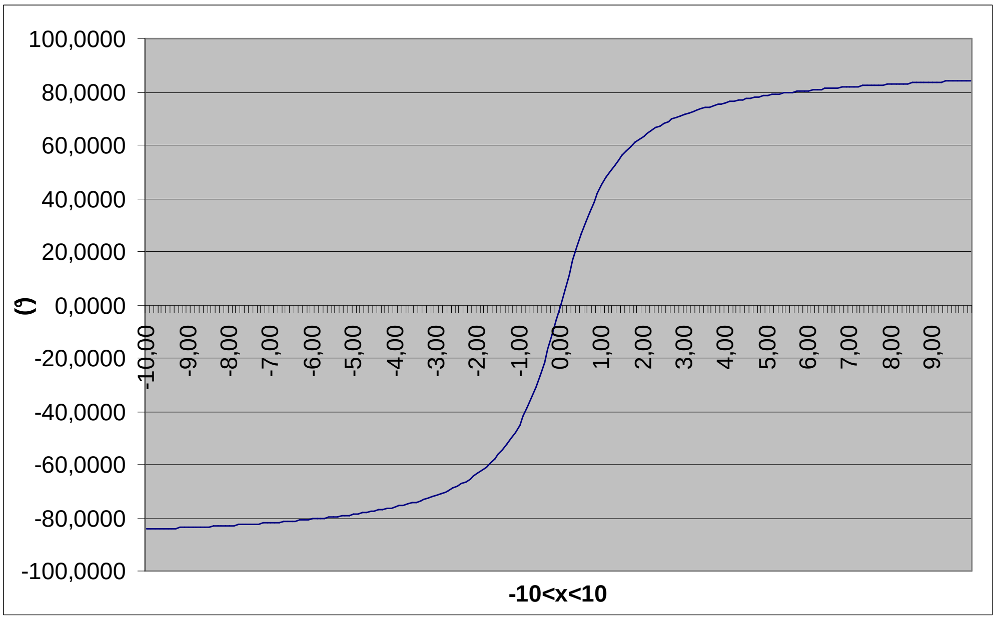


Fig. E. 10 Numerical arctangent Plotting

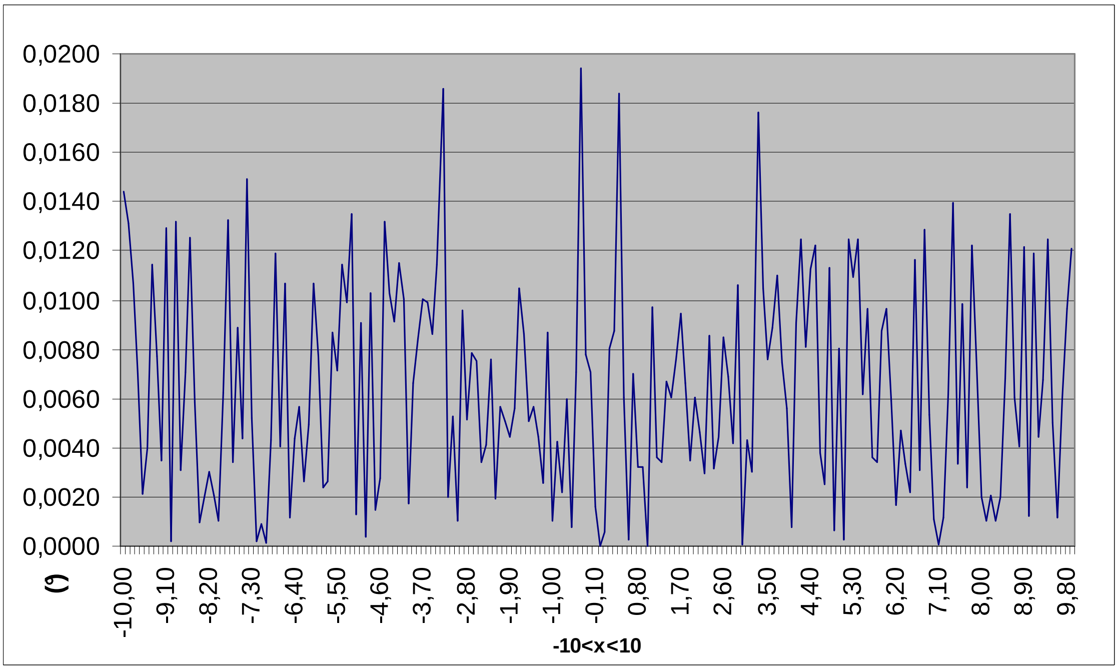


Fig. E. 11 Error between the real and the computed arctangent function

- Arcsine: The Arcsine function can be computed using the CORDIC by starting with a unit vector on the positive x axis and then rotating it so the its y component is equal to the input argument. The decision function is the result of a comparison between the input value and the y component of the rotated vector at each interaction. If c is the input argument, for each iteration the equations to be performed are:

$$
\begin{aligned}
X_{i+1} &= X_i - Y_i d_i 2^{-i} \\
Y_{i+1} &= Y_i + X_i d_i 2^{-i} \\
Z_{i+1} &= Z_i - d_i \arctan(2^{-i})
\end{aligned}
$$

Eq. E. 12

where:

$d_i = +1$ if $Y_i < c$

$d_i = -1$ if $Y_i > c$

Fig. E. 12 shows the trend of the output of the numerical function, on an input range from -1 to 1. The comparison between the real arctangent function and the computed one is shown in Fig. E. 13: the maximum error is near 0.05. The corresponding values for angles of 0°, 90°, 180° and 270° are exact.

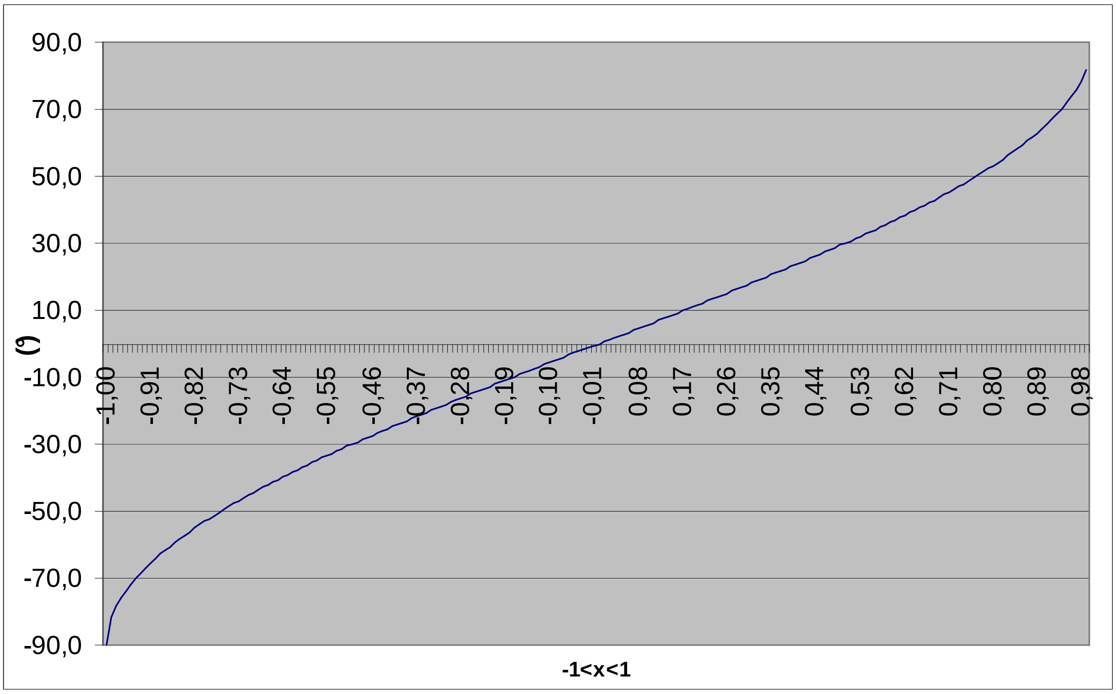


Fig. E. 12 Numerical arcsine Plotting

- Product of Trigonometric Functions: in this work the Azimuth Compensation, requires the computation of two product of trigonometric functions: Sin(Φ)Sin(Θ), Sin(Φ)Cos(Θ). These functions are computed using the rotational CORDIC algorithm for the Sine and Cosine function and then product is computed. In Fig. E. 14 and Fig. E. 16 are shown the trend of the output of the Sin(Φ)Sin(90) and Cos(Φ)Sin(90) numerical function, on an input range of Φ from 0 to 90 and maintaining constant an angle. The comparison between the real functions and the computed are shown in Fig. E. 15 and Fig. E. 17: the maximum error is near 0.017.

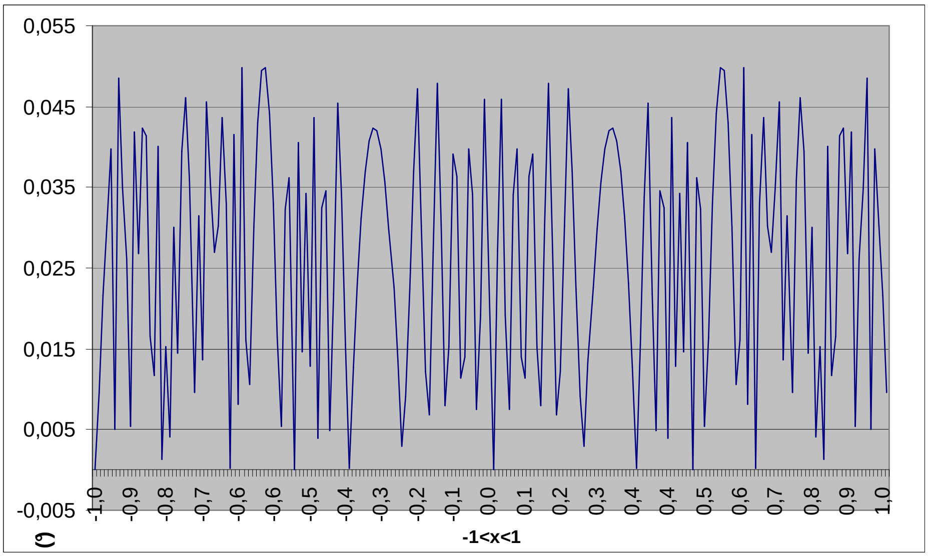


Fig. E. 13 Error between the real and the computed arcsine function

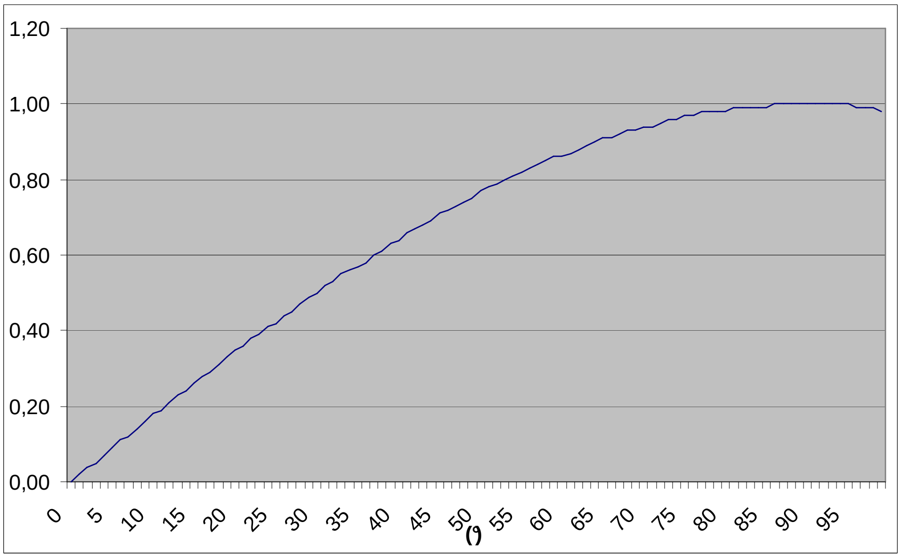


Fig. E. 14 Sin(Φ)Sin(90) Function Plotting

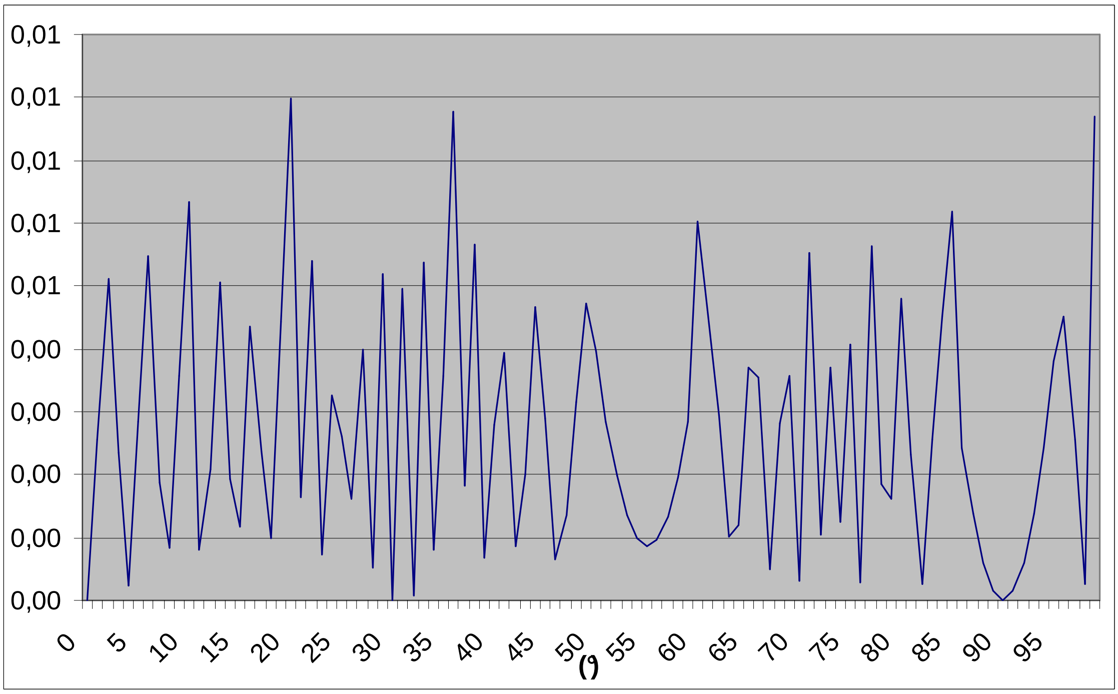


Fig. E. 15 Error between the real and the computed Sin(Φ)Sin(90) function

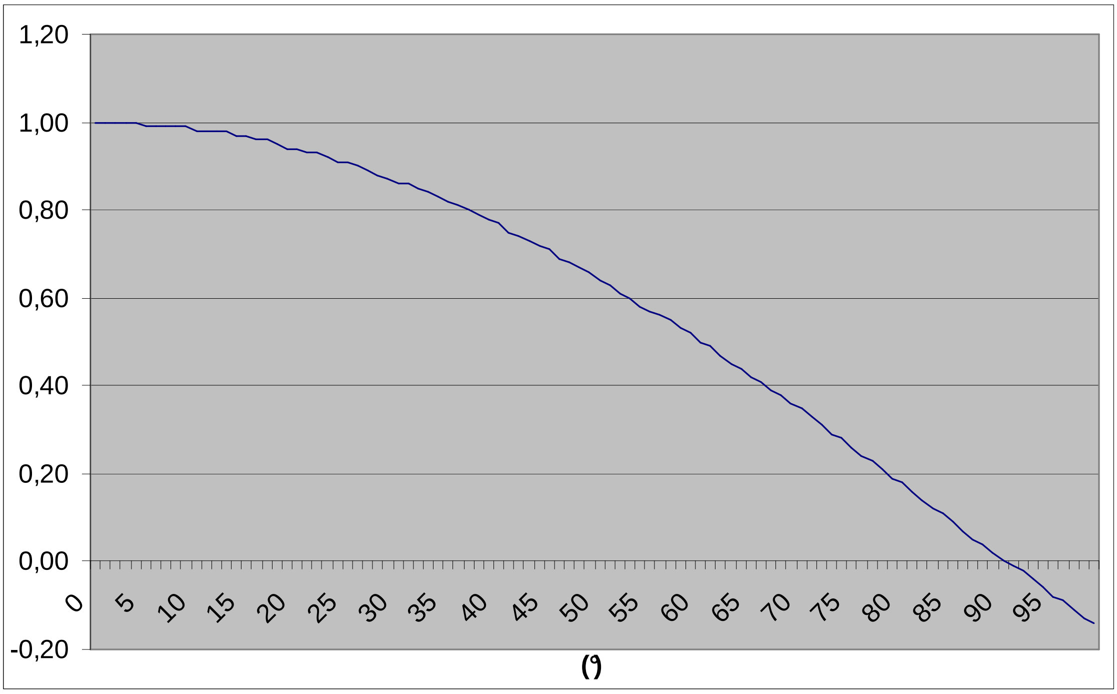


Fig. E. 16 Cos(Φ)Sin(90) Function Plotting

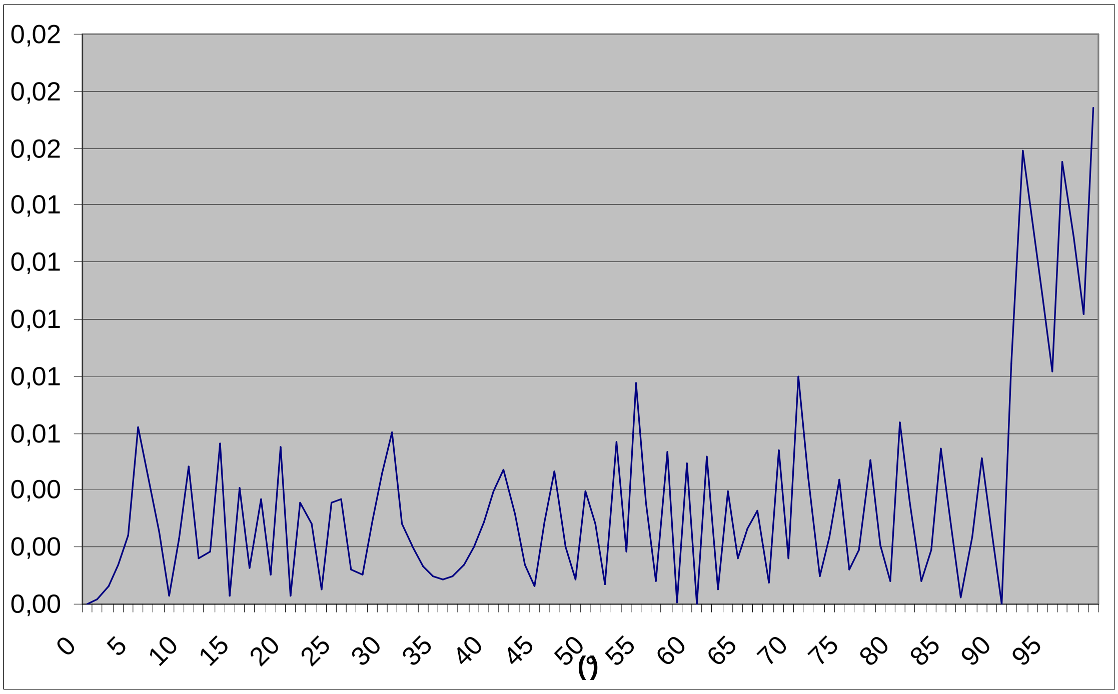


Fig. E. 17 Error between the real and the computed Cos(Φ)Sin(90)