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MONITORING ROAD SURFACE CONDITIONS USING IMU

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Contents

Abstract	ix
1 Introduction	1
1.1 Road surface monitoring instruments	4
1.1.1 Profilometer	4
1.2 Motivation	9
2 International Roughness Index	11
2.1 History	11
2.2 Definition	13
2.3 Measurement	13
2.3.1 Motivation of Correlation Equations	14
2.3.2 Information Quality Level	14
2.3.3 Quarter Car Model	18
2.4 Calculation of IRI	19
3 Inertial Measurement Unit	21
3.1 Operational Principles	22
3.1.1 Uses	24
3.2 Inertial Navigation System	25
3.2.1 Principal Sensors	25
3.3 Smartphone Sensors	26
3.4 Error	33
4 Data Analysis	35
4.1 Accelerometer Reorientation	39
Acknowledgments	41

List of Figures

1.1	Examples of Walking Profiler (left) and Disptick Profiler (right).	6
1.2	Examples of contact less profilometers mounted on vehicle.	7
2.1	International Roughness Index Scale defined by Sayers and Karamihas [13] Representing the characteristic of road roughness in function of IRI.	12
2.2	Information Quality Level Conception	15
2.3	Quarter Car Model and Frequency Response	18
3.1	Examples of IMU box.	22
3.2	Frame of car respect Yaw, Pitch, and Roll Angle.	23
3.3	Sample view of the principals sensors inside smartphone	27
3.4	Internal structure of smartphone accelerometer sensor	28
3.5	Internal structure of smartphone gyroscopes sensor	29
3.6	Triangulation technique	31
4.1	Integration using Rectangular (left) and Trapezoidal (right) methods of Sine Wave.	37
4.2	The result of double integration of a Raw Signal	38
4.3	Correct alignment of smartphone respect to the vehicle cartesian frame.	39
4.4	The result of reorientation of raw data	40

List of Tables

1.1	Classification of profilometers according to ISO wavelength range	5
1.2	Texture class in function of wavelength	5
2.1	Classification of Information by Quality and Detail	17
2.2	Golden Car Parameter	19

Abstract

In this work, it is examine how improve traffic safety through collecting and distributing road surface condition information using cheap sensors.

These information are useful for all road travelers and for the the public institution for road network maintenance. The problem considered is to detect road surface anomalies that, when unreported, can cause damage at vehicles, a reduction of driving comfort, vehicle controllable, or accident.

A system to measure some indexes like the International Roughness Index (IRI), and the location of critical points on the road surface, is been developed.

The description about the quality of the road surface is done through the analysis of a longitudinal profile.

A smartphone was used for the purpose, located inside the car, and from which some data from the principally sensors, such as the accelerometer and the GPS are both collected and processed. ProVAL (Profile Viewing and AnaLysis) software was used to calculate the final result of the IRI, while MATLAB (Matrix Laboratory) modules were processed to calculate other indexes and a first part of IRI evaluation. The obtained results are displayed on an interactive map using the Mapbox APIs, it is possible view and select one of the indexes, and get informations (such as the associated value) for each point displayed on the map.

Regarding the indexes, the obtained results for the IRI shown that there is a good relationship between the values associated with a given road segment respect IRI scale, even though it was not possible to create a correlation equation but it was just simulated, instead the critical point identifies the most damaged points on the road pavements that are within specific thresholds.

Future integration of the system will also be discussed.

Abstract

In questo lavoro, verrà esaminato come migliorare la sicurezza di viaggio su strada, attraverso la collezione e distribuzione di informazioni della superficie stradale utilizzando sensoristica a basso costo.

Informazioni sulle condizioni della superficie stradale sono utili a tutti gli utenti della strada ed alle pubbliche amministrazioni per la manutenzione della stessa. Il problema considerato che è stato considerato è quello di individuare le anomalie della superficie stradale, che quando non segnalate possono causare danni all' autovettura, provocano una riduzione del comfort di guida, una minore controllabilità dell' autovettura, oppure possono essere causa di incidenti.

In questo lavoro di tesi è stato sviluppato un sistema per misurare alcuni indici come per esempio l' Indice di Rugosità Internazionale (IRI), che rappresenta uno standard per il monitoraggio delle condizioni della superficie stradale, ed altri indicatori come per esempio la localizzazione di punti stradali molto danneggiati.

La descrizione delle condizioni della superficie stradale è effettuata tramite l' analisi di un profilo longitudinale.

Per ottenere un profilo di questo tipo è stato utilizzato per lo scopo uno smartphone, che è stato posizionato all' interno dell' autovettura, e da cui sono stati collezionati e processati alcuni dati derivanti da alcuni dei principali sensori come l' accelerometro ed il GPS.

Il software ProVAL è stato utilizzato per calcolare il risultato finale dell'IRI, mentre tramite degli script MATLAB sono stati calcolati e processati gli altri indici, ed anche parte del calcolo dell' IRI.

I risultati ottenuti sono stati mostrati all' interno di un sito web, su una mappa interattiva tramite l' utilizzo del API Mapbox, è possibile selezionare uno dei differenti indici, ed ottenere delle informazioni (come per esempio il valore associato) da ciascun punto rappresentato sulla mappa cliccando su di esso.

In merito agli indici, i risultati ottenuti per l' IRI mostrano che vi è una buona relazione tra un determinato segmento di strada e la scala dei valori IRI, anche se tuttavia non è stato possibile creare un'equazione di correlazione, ma è stata solo simulata, invece per quanto riguarda i punti critici identificano e localizzando in modo abbastanza accurato i punti maggiormente danneggiati sulla superficie stradale che ricadano all' interno di determinate soglie di calcolo.

Future integrazioni del sistema saranno discusse.

1

Introduction

The monitoring of the conditions of a road surface, such as the detection of anomalies associated with it, such as potholes, bumps, joints, level passage, small covering defects, breaks, and their proper locations, helps to improve road users' safety, from pedestrians to drivers, and has a significant impact on the road maintenance. In fact, an adequate mapping of the road infrastructure can allow workers to intervene at the most critical points, or at the most disadvantaged sections of the road itself.

For this reason, in order to offer a continuous efficient and up-to-date service, it is very important both to inform road users about the road surface quality and to obtain informations from them.

The accurate evaluation of the quality of a road surface is a critical issue: transport system could become more efficient, comfortable and, most of all, safer. In fact, the presence of different types of anomalies on a road surface can make the transport-related energy efficiency worse, by increasing fuel consumption, decay of suspensions and brakes.

Crossing one of these anomalies both generates vibrations inside the tires’ and suspensions’ system, and affects the deformation of the tire, causing energy leaks and increasing rolling resistance. In addition, an increased risk of major damage to the vehicle (broken rims, tires puncture, or damage to the car body) can occur.

Road pavement monitoring is usually carried out through a variety of instruments, most of all various types of profilometers; however, especially in the most advanced cases, a profilography¹ can be used, too. Given the high cost of these instruments, the use of mobile technologies or cheap hardware sensors is widely adopted in this area, with the aim of providing to road users the opportunity to obtain real-time informations about the road surface conditions and the traffic situation, or understand road accident cases promptly. All of that is made possible thanks to the hardware of these devices. In fact, if we mainly focus on smartphones and tablets, the majority of them uses a three-axis accelerometer to collect acceleration data, due to vehicle motion, and a GPS receiver to obtain location informations of the current specific road segment.

This work focuses on the development of a system for the road surface conditions monitoring, that makes use of inertial measurement units (also known as **IMU**), electronic hardware systems based on inertial sensors, such as the ones in our smartphones/tablets or Arduino devices, which have much lower prices than the standard instruments used for this task.

The system is based both on the reading of data collected through the smartphone, and on the post-processing elaborations of the GPS signal and acceleration data, (in which particular attention is given to vertical acceleration impulses, corresponding to high energy peaks and possibly representing an “*anomaly*” of the road surface).

After all the data has been processed, the following benchmarks for the road surface conditions are extrapolated:

- **IRI:** International Roughness Index: the international standard for road surface monitoring.
- **Critical Points:** an index that locates and labels the most critical points on the road surface.
- **Simple Acceleration Points:** an indicator able to interpret the variation of the acceleration signal on predetermined dimension tracts at different speeds.

¹The profilograph is a device used to measure pavement surface roughness

The obtained results are shown on a web-site by an interactive map.

The Introduction Chapter discusses the main instruments(1.1) used for the road surface monitoring, like profilometers(1.1.1, page: 4), and the reasons why this system was developed (1.2, page: 9).

Subsequently, the Chapter?? discusses about the *IRI*, its history and its calculation.

Chapter??, talks about the Inertial Measurement Units (IMUs), specifying what they are, their functioning and physical principles, measurement accuracy, and how they are into smartphones.

Then, Chapter?? analyzes how these data can be processed in order to get road surface conditions, what these data represent during a time series and why both a data filtering, through the analysis of the filter types that can be used to improve the processing, and a Fourier Analysis are mandatory for that purpose.

Chapter?? discusses about the work that has been done, from the data-extraction through smartphones, to how the listed-above indexes¹, whose elaboration is also explicated, are displayed on the map.

Eventually, the last Chapter??, is focused on the obtained results and on possible future extensions.

1.1 Road surface monitoring instruments

It is possible to identify two main instruments’ families for the measurement of the longitudinal road profile: *static* and *dynamic*.

The first ones perform the measurement of road profile by points, thus in a static manner, while the second ones through a dynamic method, due to their movements at high speeds; in fact, during the detection period, the vehicular traffic could be high, for this reason reaching high sampling rates could remove the noise of vehicle traffic, caused by the detection operation itself.

However, over the years, it was preferred to distinguish these families as indirect and direct instruments.

The first ones are called *Response Type Road Roughness Measuring Systems (RTRRMS)* and measure the “effect”, produced by interaction vehicle-pavement, in kinematic terms (displacement, velocity or acceleration). The second ones, called **profilometers**, return the sampled road profile for points within a defined range, instead.

1.1.1 Profilometer

Profilometers are capable of providing a digital profile of the road surface. Compared to RTRRMS, they can provide a more stable measure of road irregularities. In fact, the irregularity measures obtained by the RTRRMS systems are significantly affected by the inertial and mechanical characteristics of the vehicles on which they are mounted. However, even the measurement made by the profilometers represents an approximation of the actual road surface profile.[18]

ISO-Standard[1] identifies the following four fundamental properties to classify the profilometers:

1. Instrument mobility.
2. Detectable wavelength range
3. Nature of instrument contact
4. Operating principle of the device.

1. Instrument mobility

For this property ISO-Standard [1] provides four distinct classes.

Mobile, high speed : referees to the vehicles equipped with profilometers which can be used at a test speed greater than or equal to 60km h^{-1} .

Mobile, low speed : referees to the vehicles equipped with profilometers which can be used at a test speed smaller than to 60km h^{-1} .

Stationary in presence of traffic : placed directly on the road surface at the point you want to detect.

Stationary in absence of traffic : cannot be moved quickly from a measurement site, e.g: during the measurement on a site, that one will be closed to the traffic.

2. Detectable wavelength range

According to ISO-Standard[1], five ranges are indicated for this property, each-one distinguished by a letter:

Classes	A	B	C	D	E
Wavelength range	0.05to0.16 mm	0.2to0.5 mm	0.63to2.0 mm	2.5to50 mm	63to500 mm

Table 1.1: Classification of profilometers according to ISO wavelength range

The wavelength allows to understand the type of a road pavement. In fact, the road surface, also called *texture*, is divided among four distinct categories: microtexture, macrotexture, megatexture and irregularity. Referring to the wavelength parameters shown in the table1.1, the texture categories falls in this wavelength range:[18]

Wavelength	0.5mm	50mm	0.5m	> 0.5m
Texture	microtexture	macrotexture	megatexture	irregularity

Table 1.2: Texture class in function of wavelength

A profilometer can detect one or more wavelength classes.

3. Nature of instrument contact

According to the nature of the contact between the used instrument and the road surface, profilometers can be classified in:

- Contact Devices: the sensor that execute the reading during the measurement, establishes a real physical contact with the surface that is being investigated;
- Contact less Devices: the reading sensors do not have physical contact with the road surface, therefore the height between the profilometer sensor and the road surface point is detected thanks to the projection on that point

The operating difference is substantial: the first has a direct contact with the road surface but it can not move at high speeds during the survey, which is the main prerogative of the second type, instead.

For what concerns the affidability of the measurement, the profilometers have been classified by the World Bank as:[19]

Class 2 : devices that can make a random error during the survey;

Class 1 : very accurate devices: the possibility of measurements affected by a random error is extremely low.

Contact Profilometers

The Walking Profiler or Dipstick[13], thanks to its precision in determining road profiles, falls into the Class 1 (high precision profilometers) of the World Bank rating[19]; it is even often used to calibrate other equipments.



Figure 1.1: Examples of Walking Profiler (left) and Disptick Profiler (right).

Contact less Profilometers

These profilometers are generally made up of one or more acoustic or electromagnetic sensors and mounted on a vehicle. Nowadays, laser are the most widely used sensors.

Laser sensors are extremely delicate and expensive. A single-sensor detection, however, only provides the relative dimension of the sensor over the road surface (height between the profilometer sensor and the road surface point), which is not sufficient to know the road profile. So, generally, in order to obtain a point of the road surface itself from an higher point over the vehicle, an accelerometer is placed on the sensor structure, which provides, through a double integration, the displacements of the sensor itself in corrispondence of the road surface. The final goal of these profilometers is to extrapolate the IRI; that one, however, can not be detected only by one sensor, for the same principle of the IRI that discussed in the ??.



Figure 1.2: Examples of contact less profilometers mounted on vehicle.

4. Operating principle of the device

The easiest way to classify a profilometer is its internal operating principle.

According to this, four basic categories of profilometers were established[23].

Laser Profilometer Makes use of an appropriate filtering, which can distinguish laser light from the ambient light with an excellent contrast. Generally, a laser profilometer consists of two fundamental components:

- Source of Emission
- Capture-Transducer²

The operating principle of a laser profilometer is based on the optical principle of triangulation: the emission source projects a laser on the road surface, with a certain inclination angle to

²A transducer is a device that converts one form of energy to another one.

normal. The radius, diffused from the road surface, is received by the capture-transducer, which is also in an inclined position to receive the return signal. Then, the radius is transmitted through a lens to the transducer (sensitive photo semiconductor) [amberg1991laser]. The capture-transducer source provides a signal D , as output data, proportional to the height h (the distance between the laser incidence point on the road surface and the emission source).

Stilus Profilometer Represents the progenitor of all road surface monitoring instruments. It uses a pointed stilus, which touches the surface, and reads the small perceived irregularities, transforming them into other forms of energy. Then, an electric transducer transforms the mechanical movements of the needle into electric oscillations. These devices are equipped with a stilust needle, that is in a vertical position respect to the survey surface, which is lowered in order to physically touch the road surface. A transducer, mechanically connected to the needle, captures the magnitude of the vertical motion by transforming it into an electrical signal.

Light Sectioning Profilometer Uses a light source to produce on the road surface a little line or an high band of light, with defined edges, on the road surface. A camera resumes this line of light with a certain inclination angle and with respect to the direction of the light. In the camera output, that consists of a x-z plane, the profile is represented by the contrast line between the illuminated area and the rest of the road surface. Generally, applying this kind of profilometers requires an high-resolution image management.

Ultrasonic Profilometer Equipped with a mobile electro-acoustic sensor that emits and receives ultrasounds. These signals are first sent to the road surface, reflected and intercepted by a special microphone. The measurement is performed by considering the time between the transmission and the reception of the signal, so that the distance between the ultrasonic source and the surveyed surface can be calculated[13].

1.2 Motivation

As can be seen above, the monitoring of the conditions of a road surface is a critical issue, very useful for travelers and maintenance institutions.

With regards to travelers, it is very important to know the conditions of the road they will have to travel and their level of “comfort”: inside the vehicle, passengers perceive a certain amount of vibrations, strongly dependent on the suspension system associate to vehicle in question.

To be able to improve the perceived comfort of road users is one of the aims of this work: travel comfortable road sections is better than travel the disadvantaged ones. Disadvantages roads, in fact, increase the risk of car damages and of fuel consumption (according to some studies, a good floor pavement could improve fuel consumption by $\cong 2 - 6\%$ [11],[8]).

Furthermore, in a constantly moving society like ours, the maintenance of roads becomes a central aspect of a municipal administration. The bad maintenance of the road surface has consequences not only on the safety and health of the drivers, but also on the decor of the Commune itself. The investment that year after year the municipal authorities make for the viability, are very low. And according to [16], only a few of the major Italian municipalities can exceed a spending average pro-capite of €100,00. So, having an effective monitoring system would help both drivers and organizations, thanks to a more efficient maintenance of the critical issues related to the roads. However, the main matter is what tools have to be used in order to carry out the monitoring. In the previous section (1.1.1), in fact, we have analyzed the profilometers, which are able to directly measure the quality of the road profile, but their cost is very high and only a very small number of people can make the surface monitoring.

Thus, in this work only low-cost inertial measurement systems are used, such as the sensors of mobile devices, which, nowadays are owned by the majority of drivers, who could be able both to get almost effort-free road quality informations, and to actively participate in the collection of data.

2

International Roughness Index

The International Roughness Index (IRI) [17], was introduced in 1986 by The World Bank.[17][20] It represents the most used road roughness index to evaluate and manage road infrastructure. IRI is defined as the ratio between the sum of vehicle-wheel displacements of a standard vehicle, traveling at 80 km h^{-1} along a roadway[19].

It is calculated using the "quarter-car" mathematical model, whose response is accumulated in order to produce a roughness index with slope units (in mile^{-1} , m km^{-1} etc...) [13]

The measurement of IRI is required for all the data provided to the United States Federal Highway Administration, and it is covered by several standards from ASTM International, such as the ASTM E1364 - 95 (2005) [2]. In addition, the IRI is also used to evaluate a new pavement construction, i.e. to determine penalties or bonus payments based on its smoothness.

2.1 History

In the early 1980s, in the United States of America, some highway engineering companies identified the road roughness as the main indicator to determine the level of comfort of a road network used by different road users, from pedestrians to driver.

There were already some methodologies used to determine the roughness at that time; however, they were different among the various agencies and neither reproducible or stable over time.

For this reason, the United States National Cooperative Highway Research Program (NCHRP) started a research project in order to help the state agencies to improve the utilization of their own methodology for evaluating the road roughness[9].

The project was then continued by The World Bank[17] under the name of **International Road Roughness Experiment** (IRRE)[21], whose main goal was to determine a way to compare or to convert the data obtained from different countries, all involved in The World Bank’s projects.

After several studies, the results showed that the majority of used methodologies and instruments was able to produce significant measurements[20] of road roughness. Thus, all those methodologies were standardised and the measurement was referenced to a single, common scale.

Sayers and Karamihas [13] proposed a scale, shown below, where the IRI level is related to the characteristics of a surface and to its degradation. This scale, whose name is International Roughness Index (IRI), was, in fact, first defined and then tested only for this purpose.

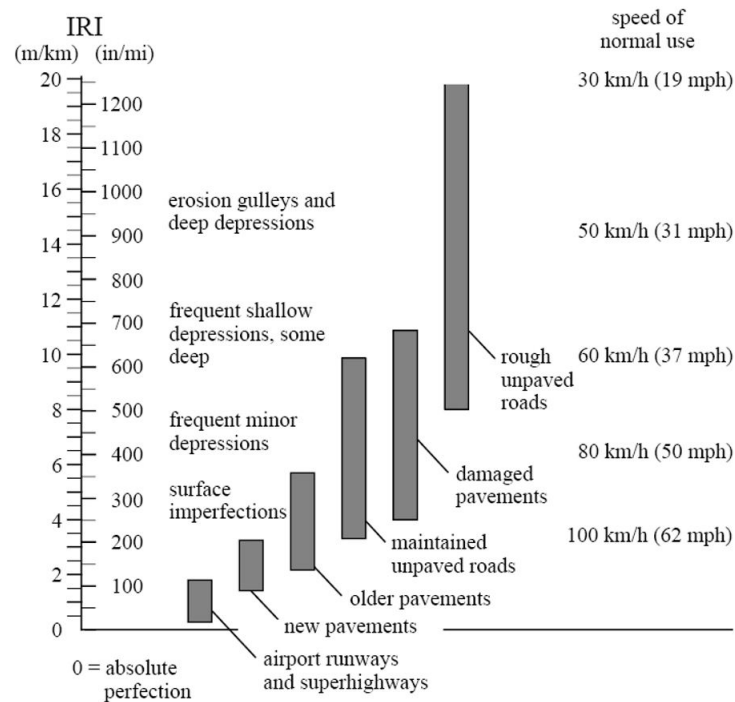


Figure 2.1: International Roughness Index Scale defined by Sayers and Karamihas [13] Representing the characteristic of road roughness in function of IRI.

2.2 Definition

IRI is defined as a mathematical model of a bidimensional road profile. This road profile represents the vertical elevation of the road surface as a function of the longitudinal distance along the travelling distance[24]. So, its aim is to show how the elevation varies depending on the length of the road in question.

The roughness measurement is difficult and complex because it depends on the vehicle characteristics and the suspension system, and also from the actual road pavement conditions. It can be calculated from profiles that are obtained by any valid measurement method, such as high-speed inertial profiling systems.

The Quarter-Car mathematical model replicates road roughness measurements that were used by highway agencies between 1970 and 1980. The IRI is statistically equivalent to the other already-in-use methodologies, i.e. the correlation among the IRI and any type of RTRRMS, is as good as the correlation between two RTRRMS measurements.

“IRI has the advantage of being repeatable, and stable over time.”

IRI scale has been chosen for compatibility with previous measures of the roughness.

The frequency content of the movement of the suspension is very similar to the frequency content of the vertical acceleration of the chassis: a very important correlation. In fact, the overall level of vibrations is similar to the overall load level of vibrations of the pavement and, despite the IRI is not suitable for the calculation of all types of vehicles, the results between these two types of data collection are almost equals, thanks to that correlation. Furthermore, this type of correlation is crucial both to demonstrate that this index can be calculated with any type of vehicle and through any inertial measuring device.

2.3 Measurement

IRI is evaluated by the road profile. It can be calculated in many ways: one of them is to use profilometers, classified as static or dynamic instruments by the World Bank, as we saw in section(1.1.1 at page 4).

Static instruments are then divided into two classes (1.1.1 at page: 6); the dynamic ones can be also grouped in another class: the Class 3 (in World Bank’s terminology).

The most common measurements are done with Class 1 instruments, capable of directly measuring the road profile. Class2 instruments are frequently used, and latest Class 3 instruments, which use correlation equations.

2.3.1 Motivation of Correlation Equations

RTRRMSs (Class 3): [13] *Calibration by correlation equation is required for a RTRRMS for many reasons*, including these important three:

1. The overall dynamic response of any particular RTRRMS vehicle will differ from the reference response. This effect can cause the “raw” measure from the RTRRMS to be higher or lower than corresponding IRI values, depending on whether the RTRRMS is more or less responsive than the reference.
2. The roadmeter in the RTRRMS generally has freeplay and other forms of hysteresis that cause it to miss counts, resulting in lower roughness measures.
3. The RTRRMS suspension motions include some effects factors other than road roughness. This induces higher roughness measures. The systematic error sources in an RTRRMS interact and are nonlinear. Their effect can change with roughness, surface type, temperature, and other environmental factors. The only way they can be taken into account is through correlation with measures of IRI obtained with a reference method (Class 1 or 2). This operation is essentially a “calibration by correlation.”

Using World Bank terminology, these correspond to Information Quality Level (IQL) 1 and IQL-3 devices, representing the relative accuracy of the measurements[6]. IQL-1 systems measure the profile direction, independent of speed, and IQL-3 systems typically have correlation equations for different speeds to relate the actual measurements to IRI. IQL-1 systems typically report the roughness at 10 to 20 m intervals; IQL-3 at 100m+ intervals.

2.3.2 Information Quality Level

As described in Bennett and Paterson[5], imagine looking out of an airplane window. Is possible recognise the landscape by a line of a river or like a highway cuts through the landscape. The plane draws nearer, and you can recognise out your neighbourhood, then your home, your car. You have been looking at the same spot throughout the descent, but the *information* available to you become more accurate. While from high above you had enough macro-level information to determine what town you were looking at, you needed a different kind of micro-level information to determine precisely where your car was

Is just experienced first hand the principle behind Information Quality Levels (IQL), introduced by Paterson and others[15].

IQL helps to structure road management information into different levels that correlate to the degree of sophistication required for decision making and methods for collecting and processing

data.

In IQL theory, very detailed data (low-level data) can be aggregated into progressively simpler forms (higher-level data), as shown in Figure 2.2. Five levels of road management have been identified for general use and are defined in Table ??.

IQL-1 represents fundamental, research, laboratory, theoretical, or electronic data types, where numerous attributes may be measured or identified. IQL-2 represents a level of detail typical of many engineering analyses. IQL-3 is a simpler level of detail, typically two or three attributes, which might be used for large production uses like a network-level survey or where simpler data collection methods are appropriate. IQL-4 is a summary or a key attribute which has use in planning, or in low-level data collection. IQL-5 represents top-level data such as key performance indicators, which typically might be combined key attributes from several elements of information. Furthermore higher levels can be defined as necessary.

At IQL-1, pavement conditions are described by twenty or more attributes. At IQL-2, these would be reduced to 6-10 attributes, one, or two for each mode of distress. At IQL-3, the number of attributes is reduced to two to three, particularly, roughness, surface danger, and texture resistance. At IQL-4, all of the lower-level attributes may be condensed into one attribute, Pavement Condition (or state or quality), which may be measured by class values (good, fair, poor) or by an index (e.g., 0-10). An IQL-5 indicator would combine pavement quality with other measures such as structural adequacy, safety aspects, and traffic congestion representing a higher order information, such as road condition.

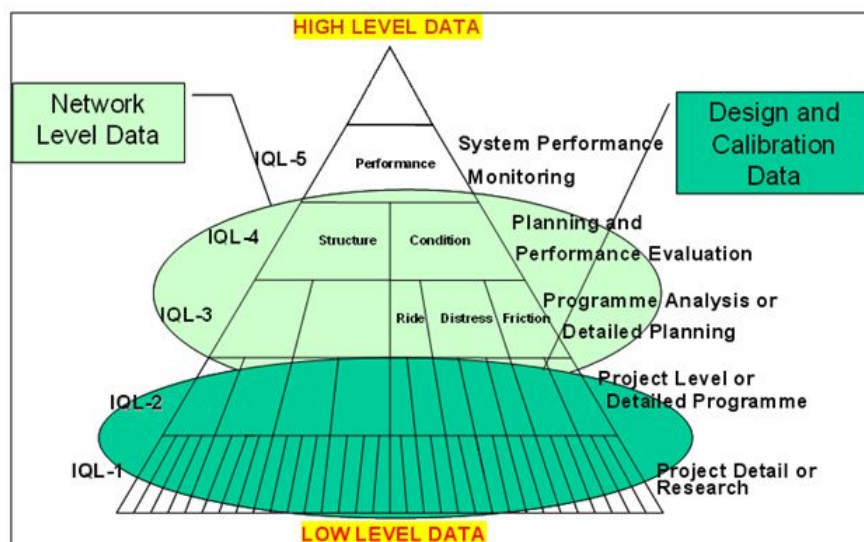


Figure 2.2: Information Quality Level Conception

From the previous definition of IQL is possible identify three observation.

- The higher the decision-level, the higher the IQL. Information at IQL-4 or IQL-5 is appropriate for performance indicators and road statistics, because of they are, easily understand without much technical background. At the project-level, however, the appropriate IQL depends much on the standard of the project and the resources of the agency. For example, IQL-3 is usually sufficient for a rural road or a small local agency. For most agencies and main roads, IQL-2 is typical, but for expressways, also IQL-1 may be used in some instances. The criteria to select the appropriate IQL depends if the decision is altered by having more detailed information, and so with a different IQL level.
- Primary data collection at a low-level (detailed) IQL typically costs more and involves more sophisticated instrument than the collection of higher IQL data. So, the IQL for primary data collection that is appropriate to a given agency and situation depends on the financial and physical resources, skills, cost, speed or productivity, the degree of automation, complexity, all to obtain a sustainable method, such as the regular operation of a road management system.
- A higher level IQL often represents an aggregation or transformation of the lower level IQLs. When there is a specific rule or formula for conversion, from IQL-2 into IQL-3, then the information is reproducible and reliable. Thus, when the appropriate IQL is chosen, the data can be re-used through a transformation to the higher IQLs and this avoids the need for repeating surveys and saves cost.

According to Bennett and Paterson[5] was defined the following table of the amount of detail of each IQL level.

IQL	Amount of Detail
1	Most comprehensive level of detail, such as that which would be used as a reference benchmark for other measurement methods or in fundamental research. Would also be used in detailed field investigations for an in-depth diagnosis of problems, and for high-class project design. Normally used at project-level in special cases and unlikely to be used for network monitoring. Requires high level skill and institutional resources to support and utilize collection methods.
2	A level of detail sufficient for comprehensive programming models and for standard design methods. For planning, would be used only on sample coverage. Sufficient to distinguish the performance and economic returns of different technical options with practical differences in dimensions or materials. Standard acquisition methods for project-level data collection. Would usually require automated acquisition methods for network surveys and use for network-level programming. Requires reliable institutional support and resources.
3	Sufficient detail for planning models and standard programming models for full network coverage. For project design, would suit elementary methods such as catalogue-type with meager data needs and low-volume road/bridge design methods. Can be collected in network surveys by semi-automated methods or combined automated and manual methods.
4	The basic summary statistics of inventory, performance, and utilization that are of interest to providers and users. Suitable for the simplest planning and programming models, but for projects is suitable only for standardized designs of very low-volume roads. The simplest, most basic collection methods, either entirely manual or entirely semi-automated, provide direct but approximate measures and suit small or resource-poor agencies. Alternatively, the statistics may be computed from more detailed data.

Table 2.1: Classification of Information by Quality and Detail

2.3.3 Quarter Car Model

For the calculation of the IRI index, it is necessary to define a standard reference vehicle,[13]. This vehicle, for reasons of simplifying the index calculation process, was identified in the quarter-car model shown in Fig. 2.3.3. This model is two-dimensional because only movement in the Z direction is taken into consideration. This model schematizes the vehicle with a sprung mass and a unsprung mass, connected by a shock absorber and a suspension, identified by a spring with own elastic constant and connected to the road pavement through the tire, also simplified with a spring of an elastic constant[13].

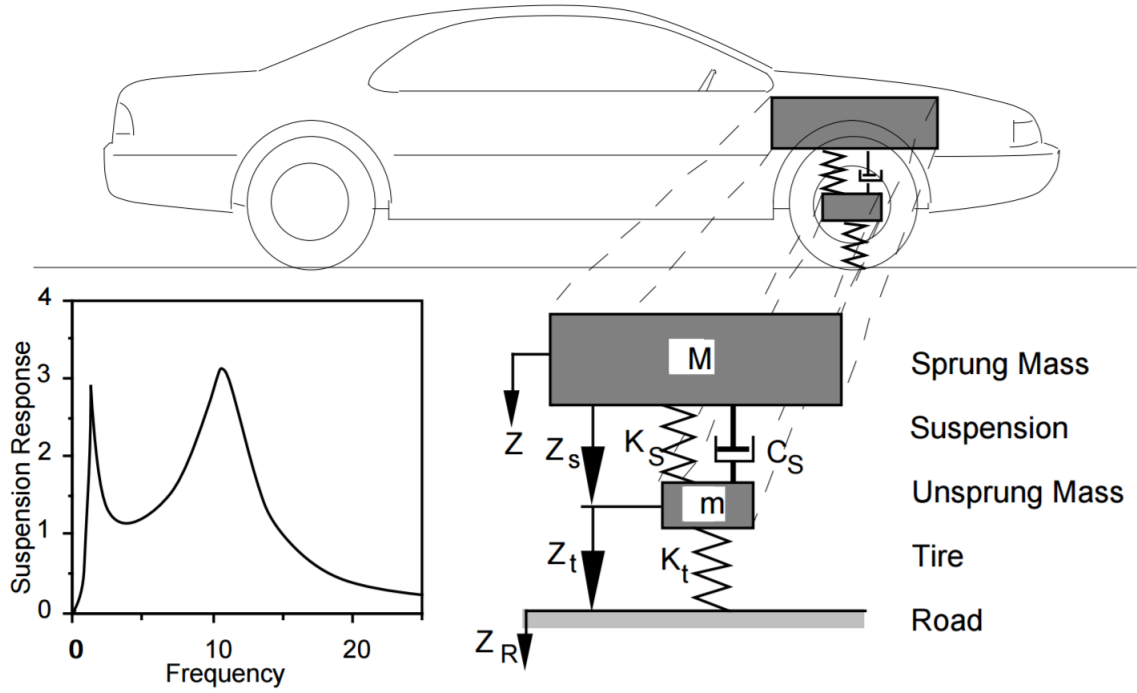


Figure 2.3: Quarter Car Model and Frequency Response

[10]However the roughness is seen as deviations in elevation (displacement inputs), slope (velocity inputs), or change of slope (acceleration inputs) the quarter car responds in a defined manner. The response can be mathematically described with a relatively simple set of dynamic equations known as a quarter-car simulation.

$$\begin{cases} \ddot{Z}_s m_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s(Z_s - Z_u) = 0 \\ -\ddot{Z}_s m_s + \ddot{Z}_u m_u + K_t(Z_u - Z_p) = 0 \end{cases}$$

Where the symbols represents:

Z_s = The quote of sprung mass relative to the static equilibrium position,

Z_u = The quote of unsprung mass relative to the static equilibrium position,

Z_p = Road pavement height at fixed point,

m_s = Sprung mass,
 m_u = Unsprung mass,
 k_s = Elastic subsuspension constant,
 k_u = Elastic tire constant,
 C_s = Damper damping constant.

The system of two second order differential equations can be simplified by normalizing the parameters m_u , k_t , k_s , c_s from the suspended mass m_s , according to the positions,[10]:

$$\mu = \frac{m_u}{m_s}; k_1 = \frac{k_t}{m_s}; k_2 = \frac{k_s}{m_s}; c = \frac{C_s}{m_s}$$

Thus, the system becomes a system of four differential equations of the first order that in matrix form can be expressed as:

$$\dot{Z} = AZ + BF_a + \dot{Z}_p$$

Where vector Z represents the vector of the state variables, i.e. the variables that are needed to fully define the state of the system.

For the standard vehicle used in the IRI definition, the average values of American vehicles were obtained, this value obtained are called **“Golden Car”**. [13]. It presents the following coefficient values for the quarter of a vehicle:

Parameter	Value
$c =$	$6.0s^{-1}$
$K_1 =$	$653s^{-2}$
$K_2 =$	$63.3s^{-2}$
$\mu =$	0.15

Table 2.2: Golden Car Parameter

About the frequency response of the model, at very low frequencies (corresponding to long wavelengths in the road) the suspension response is zero because the wheel and the vehicle body move up and down together. The response is maintained up through frequencies near 10 Hz where axle resonance occurs. Above the axle resonant frequency the response again drops to zero as the road bumps simply deflect the tire without producing significant suspension stroke. The frequency response of the quarter car extends from approximately 0.5 to 20 Hz .

2.4 Calculation of IRI

Note the values, instant for instant, of the displacement velocities Z_s and Z_u obtained by integrating from the system of equations describing the motion of the Quarter car model, the

calculation of the IRI is performed by the formula:

$$IRI = \frac{1}{L} \int_0^{\frac{L}{V}} |\dot{Z}_s - \dot{Z}_u| dt$$

Where L is the profile length and V is the standard speed of 80km h^{-1} . Generally IRI is measured in mm km^{-1} or in mi^{-1} . This index, as defined, is comparable to two profiles, meaning that if a 500 m profile has an IRI index of 100 mm km^{-1} and the next 500m profile has an IRI index of 200mm km^{-1} , The entire 1000m profile will have an IRI of 150 mm km^{-1} , and this is one of the most important features of that index[13].

The measurement and calculation procedure of IRI are also based on the following principles:

- A single longitudinal profile with sample interval not longer than 300 mm is measured.
- The measured profile is smoothed with a 250mm base length moving average filter known as IRI filter.
- The slope between consecutive elevation points is considered to be constant.

The IRI index is calculated by filtering the measured profile with the quarter car filter, at a simulation speed of 80km h^{-1} , so that it provides a summary value of the slope, as it is recorded by the vehicle. The algorithm used for the IRI value calculation uses a theoretical filter describing the quarter car theoretical response to pavement surface irregularities.

As mentioned briefly earlier, the IRI index has been defined to classify road pavements in terms of driving comfort in the vehicle and damage to the pavement. Indeed, the correlation between IRI and comfort or damage is remarkable[10].

3

Inertial Measurement Unit

Inertial sensors, called Inertial Measurement Unit (**IMU**), is an electronic device of measurement that allows to estimate specific force, angular velocity and sometimes magnetic field of a body from the inertial forces that the body experiences. Its operation principle is based on the use and combination of forces from accelerometers, gyroscopes, and sometimes magnetometers

The inertial technology is based on the first two Newtons laws.

The first law, affirms that the movement of a body is uniform and linear unless an external force is acting on it.

The second law, defines that this force exerted on the mass will produce a proportional acceleration.

$$\mathbf{F} = m\mathbf{a}$$

These relationships represent a *measurement principle* from which can be developed sensing devices able to measure the movement of bodies. If we know the magnitude and direction of the forces applied to a body and its mass, we can know its acceleration. Speed and position are obtained from the acceleration versus time, by first and second mathematical integration.

Recent developments allow the production of IMU compatible with GPS devices. An IMU allows a GPS receiver to operate when GPS signals are not available, e.g. in tunnels, buildings or in the presence of electronic interference[12]

3.1 Operational Principles

An IMU is a single unit into an electronics module which detects and collects angular velocity using one or more gyroscopes, linear acceleration data using one or more accelerometers and sometimes magnetic fields by using one or more magnetometer.

A typical configuration of IMU contains two separate sensors.

First is the three-axial accelerometer. It generates three signals describing the accelerations along each of its axes. Second is the three-axial gyroscopes, it outputs three analogue signals, and describe the vehicle angular velocity for each of the sensor axes.

Another possible configuration, contains also a three-axial magnetometer that produced three signal along each axis that describing the magnetic-field around the body.

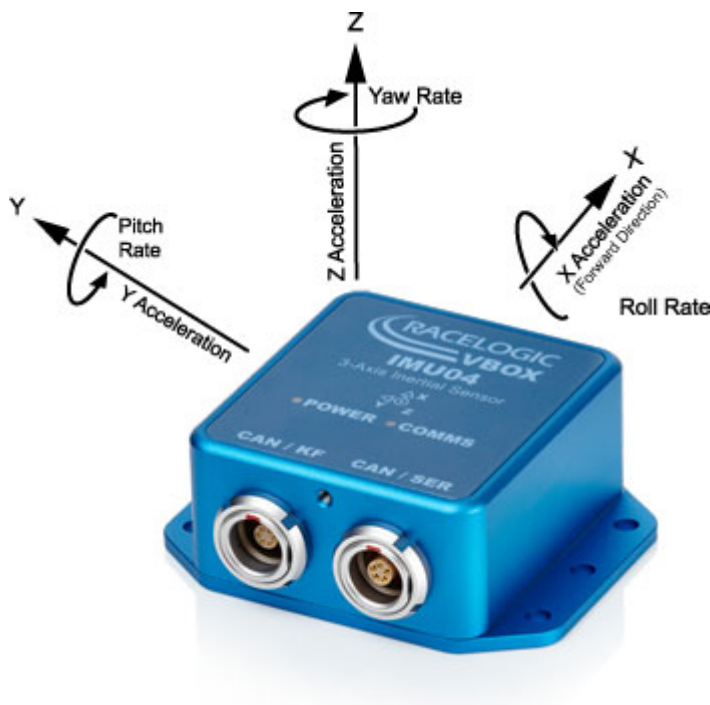


Figure 3.1: Examples of IMU box.

The three axes around the sensors that produce the signals are **pitch**¹, **roll**², and **yaw**³, in fact, IMUs works by detecting the changes in pitch, roll, and yaw.

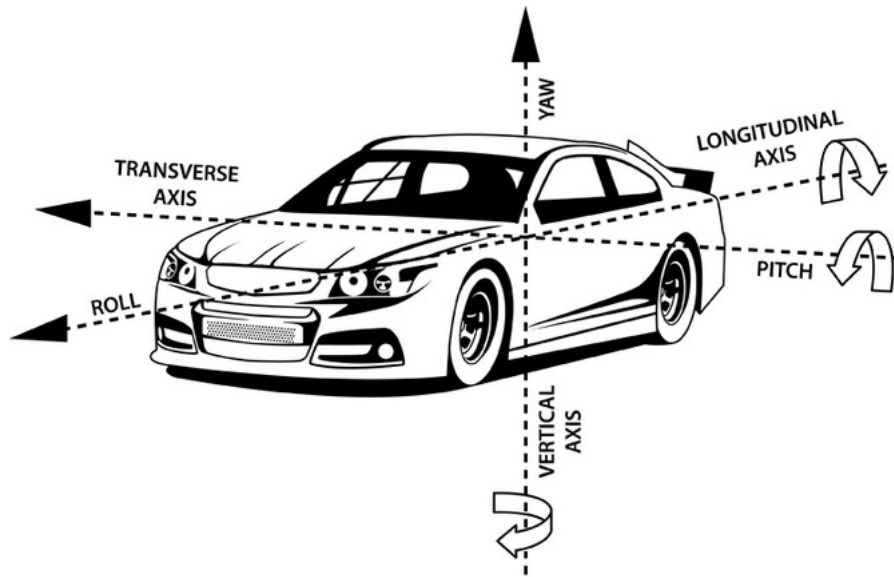


Figure 3.2: Frame of car respect Yaw, Pitch, and Roll Angle.

¹The pitch axis (also called lateral axis) has its origin at the center of gravity and is directed to the right

²The roll axis (or longitudinal axis) has its origin at the center of gravity and is directed forward

³The yaw axis (Vertical axis) has its origin at the center of gravity and is directed towards the bottom of the vehicle

3.1.1 Uses

Nowadays, IMU are often incorporated into Inertial Navigation Systems (INS), which use the raw IMU measurements, and after a processing and combination of these, is possible determine attitude, angular velocity, linear velocity and position relative to a global reference frame⁴, in our case the frame of the vehicle, as is shown in the Figure??.

The IMU are highly applied for the navigation and control of the military, civil, and many commercial vehicles for real-time monitoring, and for geodetic navigation through post-processing of data.

Finding, ample space for use in space navigation systems, cars, ships, planes and aeroplanes.

The process to obtain velocity from acceleration and position from velocity, is known as dead reckoning.⁵ In land vehicles, an IMU can be integrated into GPS based automotive navigation systems⁶ or vehicle tracking systems⁷, giving at the system a dead reckoning capability and the ability to gather as much accurate data as possible about the vehicle’s current speed, turn rate, inclination and acceleration.

Besides navigational purposes, IMU serve as orientation sensors in many consumer products. Smartphones and Tablets contain IMU as orientation sensors. Fitness trackers and other wearable devices may also include IMU to measure motion. They are a competing technology for use in motion capture technology[25].

⁴a reference frame consists of an abstract coordinate system and the set of physical reference points that uniquely fix the coordinate system and standardize measurements.

⁵The idea is to start from a known state (e.g. holding still) and calculate a new state (e.g. moving up or down) based on a measurement that indicates change, although it does not actually give you the info you want directly.

⁶An automotive navigation system is part of the automobile controls or a third party add-on used to find direction in an automobile. It typically uses a satellite navigation device to get its position data which is then correlated to a position on a road

⁷A vehicle tracking system combines the use of automatic vehicle location in individual vehicles with software that collects these data for a comprehensive picture of vehicle locations

3.2 Inertial Navigation System

An inertial navigation system (INS) is able to process the reported IMU data by a processor, like motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity of a moving object without the need for external references[3].

The guidance system could show at pilot where the vehicle is located geographically at a certain moment, as with a GPS navigation system, but without the need to communicate with or receive communication from any outside components, such satellites. External sources are however used in order to correct drift errors.

Recent advances in the construction of microelectromechanical systems (MEMS)⁸ have made the possibility to manufacture small and light inertial navigation systems, they are widely used in mobile devices, thanks to their small size without compromising performance.

3.2.1 Principal Sensors

The main sensors of IMU system as we have discusses in the introduction3.1 are the Accelerometer and Gyroscopes:

Accelerometer : measure the linear acceleration of the moving vehicle in the sensor or body frame, but in directions that can only be measured relative to the moving system (the accelerometers are fixed to the system and rotate with the system, but are not aware of their own orientation). This can be thought as the ability of a blindfolded passenger in a car to feel themselves pressed back into their seat as the vehicle accelerates forward or pulled forward as it slows down; and feel themselves pressed down into their seat as the vehicle accelerates up a hill or rise up out of their seat as the car passes over the crest of a hill and begins to descend. Based on this information alone, they know how the vehicle is accelerating relative to itself, that is, whether it is accelerating forward, backward, left, right, up (toward the car’s ceiling), or down (toward the car’s floor) measured relative to the car, but not the direction relative to the Earth, since they did not know what direction the car was facing relative to the Earth when they felt the accelerations. Note that the accelerometers will actually detect a force that is directed in the opposite direction from the acceleration vector.

Gyroscopes : measure the angular velocity of the sensor frame with respect to the inertial reference frame. By using the original orientation of the system in the inertial reference

⁸MEMS is the technology of microscopic devices, particularly those with moving parts.

frame as the initial condition and integrating the angular velocity, the system’s current orientation is known at all times. This can be thought of as the ability of a blindfolded passenger in a car to feel the car turn left and right or tilt up and down as the car ascends or descends hills. Based on this information alone, the passenger knows what direction the car is facing but not how fast or slow it is moving, or whether it is sliding oblique.

An INS system is useful for a real-time monitoring but is possible getting the information about the velocity and position after processing IMU data when the travel is finished and the data are sent to a server or are stored into a device.

3.3 Smartphone Sensors

Nowadays, smartphones are widely used in the world, and they are equipped with many sensors such as an accelerometer, gyroscope, touch-screen, ambient light sensor, proximity sensor, magnetometer, barometer, heart pulse rate monitor, for the purpose of this work the main sensor used is the accelerometer. Smartphone sensors are very cheap, and their size is getting smaller and smaller, in fact, they are also called Micro Electro-Mechanical-Systems (MEMS), motion sensors, and can offer great data results if compared with more both expensive and professional, so the information given by IMU is useful if the relations between the smartphone reference system, the vehicle reference system and the world reference system are known, in fact, by getting this information in real-time from the motion sensor is possible create an inertial navigation system by sensor data or process after the travel is finished if the data are stored, in fact there are many applications to allow the registration of the smartphone sensors data, it also be useful combine the use of the GPS.

These sensors are capable of providing raw data with high precision and accuracy, and are useful to monitoring three-dimensional device movement or positioning, or changes in the ambient environment near a device.

Usually a smartphone platform supports three broad categories of sensors:[4]

- Motion sensors: they measures acceleration forces and rotational forces along three axes. This category includes accelerometers, gravity sensors, gyroscopes, and rotational vector sensors.
- Environmental sensors: they measures various environmental parameters, such as ambient air temperature and pressure, illumination, and humidity. This category includes barometers,

photometers, and thermometers.

- **Position sensors:** They measure the physical position of a device. This category includes orientation sensors and magnetometers.

Simplified view of a smart-phone board

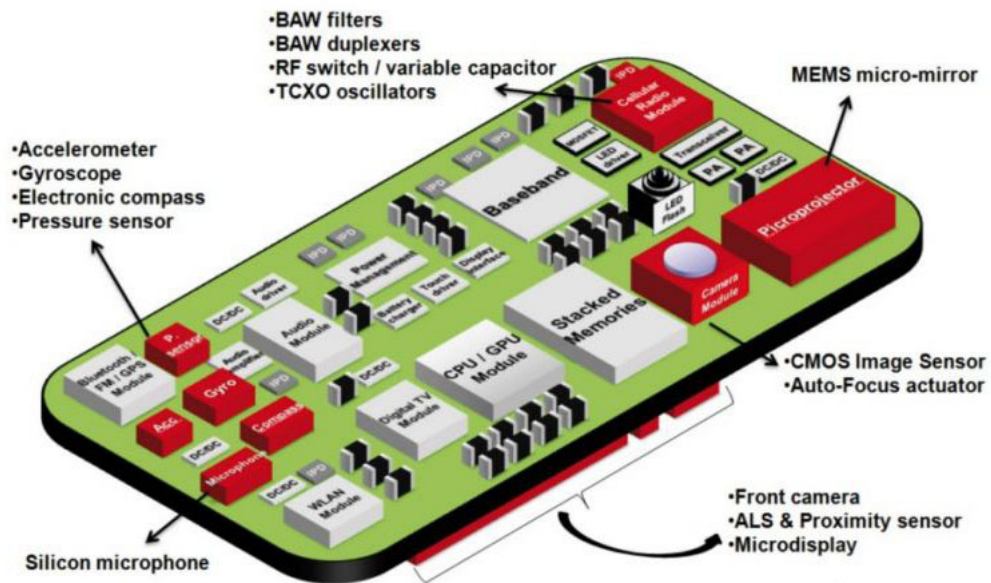


Figure 3.3: Sample view of the principals sensors inside smartphone

Accelerometer

Smartphones are builded with an accelerometer sensor.

They are sensitive to both linear acceleration and the local gravitational field, for each of the three-axes.

The accelerometer measures the acceleration of a smartphone against free fall, so allowing an application both determine the movement of the smartphone and its inclination.

The sensor consists of two components, a fixed and a mobile.

The second, moving according to the vibrations received, allows the first to measure and process the received data, then the distance variation between the capacitor⁹ armatures (so the electric capacity variation) will be used to determine the variation of the forces of acceleration which is subjected a device.

A special circuit records the variations created within the capacitor (these capacitors armatures

⁹A capacitor is a passive two-terminal electrical component that stores electrical energy in an electric field.

are, made up of a moving mass and the fixed structure of the device) so that it can generate an electrical signal, proportional to the displacement of a mass. The measurement is done for each axis (x , y , and z .), and it will be possible to measure the three-dimensional acceleration variation.

The figure below3.5 show the internal structure of accelerometer sensor.

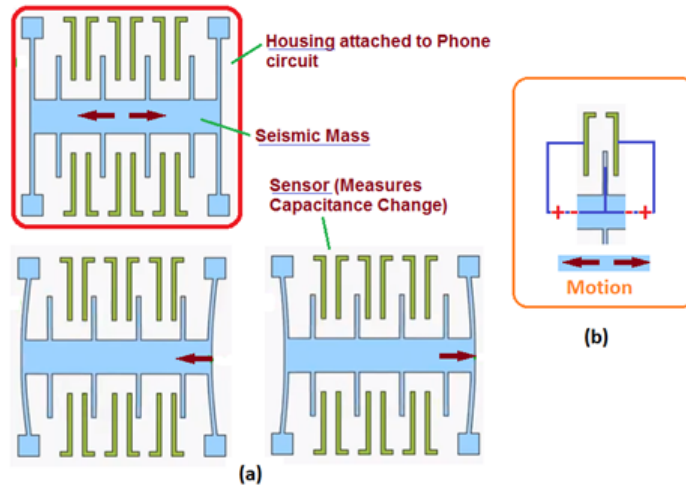


Figure 3.4: Internal structure of smartphone accelerometer sensor

Gyroscopes

The gyroscopes detects the current orientation of the device, or changes in the orientation.

Orientation can be computed from the angular velocity detected by the gyroscope, expressed in rad/s on the three-axis.

A triple axis MEMS gyroscope, can measure rotation around the three axes: x , y , and z . When the gyro is rotated, a small resonating mass is shifted as the angular velocity changes. This movement is converted into very low-current electrical signals that can be amplified and read by a host microcontroller. The figure below show the internal structure of gyroscopes inside smartphone.

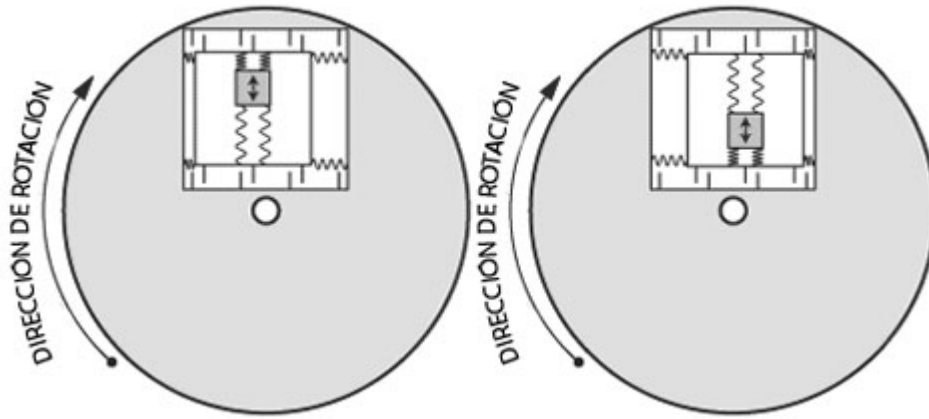


Figure 3.5: Internal structure of smartphone gyroscopes sensor

GPS

All smartphones have GPS (Global Positioning System acronym), it is able to give our position. In good condition a GPS receiver indicates the location with an accuracy of about 10 m. The aim of GPS system is to provide the coordinates of our position in terms of latitude, longitude and altitude.

The GPS system technically consists of 3 levels called segments:

Spatial Segment is given by 31 satellites rotating around the earth and which are the heart of GPS operation. The satellites travel to over 20.000 km from the ground.

Control Segment is provided by the main control station (and one of the reserve). The US military aircraft control satellites and carries out all related maintenance operations.

User Segment is simply the device with integrated GPS: navigator, smartphone, tablet, etc..

GPS can find our position on earth knowing:

- The distance from at least 3 satellites
- The position of the satellites

The GPS receives the radio signal from the satellite that orbits in its vicinity and thanks to this signal, can calculate its distance using the simple formula:

$$Distance = Time * Speed$$

Speed: Satellite signal travels at speed of light ($299,792 \text{ km s}^{-1}$)

Time: To find the time value, the satellite and the GPS of device (receveir) start from a common base signal, when the receiver has to calculate the position, receives from the satellite the signal, but having to travel thousands of kilometers the signal will come with a certain delay, this delay is the travel time were looking for. The signal usually arrived about in the order of *100ths* of a second. By multiplying the speed and travel time, our receiver will have distances from the satellites. To this end, the satellite sends the track of its position over time (which is stored in our device)

Once we have the exact distances from the satellite and its position, is possible find ours position on the earth. Triangulation technique is used for the purpose, through the information from the 3 satellites we solve a system of 3 equations with 3 unknowns: Latitude, Longitude and Altitude.

In general, the triangulation technique allows to find exactly our position as the intersection of three sphere having a radius equal to the distance of our point from the point of reference.

Actually, the intersection of the spheres produces two points in the space (one up and one down), but the problem is solved because considering the Earth sphere and inserting it into the geometric calculation we will have a single point on the earth surface representing our current position. As shown in the figure3.6 below.

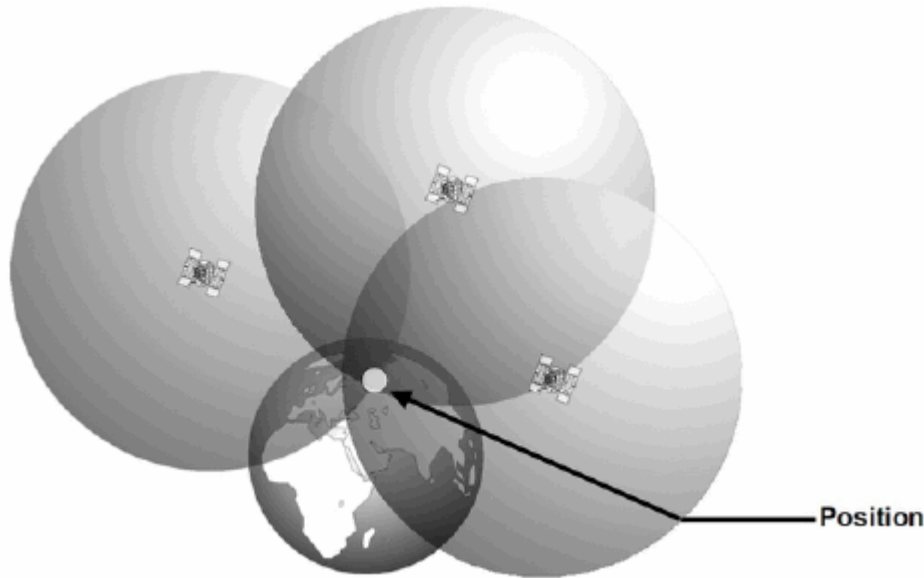


Figure 3.6: Triangulation technique

There are 3 types of modes available on smartphones to get the GPS signal:

- **High Accuracy:** uses data networks, Bluetooth, Wi-Fi or GPS to get the location
- **Battery Saver:** uses data networks, Bluetooth or Wi-Fi to get the location
- **Only Device:** only uses the GPS sensor signal.

GPS works at 1 Hz once connection is established, thus the application records a sample of data once per second on average

Other Sensors

However, there are still many sensors available within smartphones, and they are:

Magnetometer : detect magnetic fields. (compass applications use this to point at the planet’s north pole)

Proximity sensor : it is placed near the earpiece of a phone. During a call, this sensor lets the system know that you’re most probably in a call and that the screen has to be turned off.

Light sensor : measures how bright the ambient light is. The phone’s software uses this data to adjust the display’s brightness automatically.

Barometer : measures atmospheric pressure. Data measured by it is used to determine how high the device is above sea level, which in turn results in improved GPS accuracy.

Thermometer : measures ambient temperature. Some handsets might have more than one of them(to monitor the temperature inside the device and its battery)

Pedometer : is a sensor used for counting the number of steps that the user has taken.

Heart rate monitor : measure one’s pulse, and it does that by detecting the minute pulsations of the blood vessels inside one’s finger.

Fingerprint sensors : the sensor is most convenient to use, as it does not require swiping in order to read fingerprint data.

3.4 Error

The major disadvantage of using IMU for navigation is that they typically suffer from accumulated error. Because the guidance system is continually integrating acceleration respect to the time to calculate velocity and position, any measurement errors, however small they are, are accumulated over time. This leads to “*drift*”: an ever-increasing difference between where the system thinks it is located and the actual location. For the integration, a constant error in acceleration results in a linear error in velocity and a quadratic error growth in position.[22]

Signals from the IMU are processed by signal processing at a very high rate. For example, in a 100Hz IMU, the sample period represents the total motion of the IMU over 10 millis. To reduce the effect of the measurement errors, they must be understood, estimated and then corrected. A well-designed system filter estimates and removes errors from the IMU measurements, reaching a higher attitude accuracy and longer solution stability .

The general error terms.

Repeatability : the ability of the sensor to produce the same output for the same repeated input, assuming all other conditions are the same.

Stability : the ability of the sensor to produce the same output, over time, for the same constant input.

Drift : the change of the output over time (zero drift is the change over time with no input).

Even when an IMU is stationary, it still measures forces. These measurements are the result of the IMU measuring forces in an inertial frame, a reference, fixed in space and time. Gravity acts in the inertial frame. The strong effect of gravitys acceleration can be measured by the accelerometers and is always significant when operating near the Earths surface. Not all of these errors are relevant for all IMUs. Some of the error terms are too small to create a significant difference in the final solution. A key to having a high-performance processing system is to understand what the errors are in the system and developing ways to reduce or remove the errors and error sources, so a proper filter system needs to be developed, however during the integration the principal error is caused by the noise of the input IMU signal.

4

Data Analysis

As discussed in Chapter?? in the Error section(?? on page ??). IMU, during measurement suffer from accumulated error.??

The measurement along the pathway of road surface consists of a sampling of measurements at specific time intervals (usually in the order of milliseconds).So the road profile can be seen as an electronically acquired digital signal and consequently it is necessary clean up the signal from the noise¹, it may also be useful to delete certain information in the signal that is not of interest, or correct it from the drift (??).

This cleaning procedure, also called filtering,it is used in the theory of signal analysis. It is an essential aspect in the evaluation of the profile, [13]. In brief, a digital filter represents a procedure that transforms a series of numbers into a new series of numbers, [13].

From the measurement obtained by the sensors, particular attention is given to the vertical acceleration signal and to the rotation vectors.

The rotation vectors will be useful for reorienting the signals obtained from the smartphone[4] respect to the vehicle axes, while the vertical acceleration signal will be subject to various filtering operations depending on the final index to be obtained.

¹An unknown modifications that a signal may suffer during capture

First of all, it is necessary to pay some attention to some dynamics² physical principles, about the operations that can be done, on the acceleration signal to get the position and vice-versa.

Given a position versus time of an object, $x(t)$, the velocity, $v(t)$, can be found by taking the first derivative.

$$v(t) = \frac{dx}{dt}$$

Acceleration, $a(t)$, can be found by taking the second derivative of position or first derivative of velocity.

$$a(t) = \frac{d^2x}{dt^2} = \frac{dv}{dt}$$

However, is interesting to reverse this process and find the position signal given an acceleration signal. To do that, a double integration must be performed on the acceleration signal. In principle, using double integration on an acceleration signal to get a position signal, the initial position and initial velocity must be known. After the first integration, the initial velocity should be added to the result, as the initial position should be added after the second integration. These operations are illustrated in the following equations

$$v(t) = v(t_0) + \int_{t_0}^t a(\tau) d\tau \quad (4.1)$$

Where:

Symbol	Description
t_0	Initial Time
$v(t_0)$	Initial Velocity

To get the position signal from velocity, is used the followed formula:

$$x(t) = x(t_0) + \int_{t_0}^t v(\tau) d\tau. \quad (4.2)$$

Where:

²branch of mechanics that deals with the study of the motion of bodies and their causes or, more concretely, of the circumstances that determine and modify it

Symbol	Description
t_0	Initial Time
$x(t_0)$	Initial Position

Therefore, for a double integration of the acceleration, the two initial conditions (velocity and position) must be known to avoid integration errors. However, the only way to get these initial conditions is through direct measurement, which is often impractical or unobtainable. By data filtering, it is developed an approach that does not require knowledge of initial conditions.

To perform a numerical integration it is necessary to choose one integration algorithm of the many existing. The acceleration signal is sampled, making it a discrete function of time having a sampling frequency, f_s , associated with it. The easiest way to perform numerical integration is to use the rectangular integration method. This method uses an accumulator to sum all past sampled inputs and the current input sample and divide by the sampling rate. Rectangular integration is represented by the following difference equation:

$$y(n) = \frac{1}{f_s} \sum_{k=0}^n x(n-k) = y(n-1) + \frac{1}{f_s} x(n)$$

Another numerical integration method uses the trapezoidal rule. The results are more precise with this method than the rectangular method. The difference equation for trapezoidal integration is:

$$y(n) = y(n-1) + \frac{1}{2f_s} [x(n-1) + x(n)], n > 0$$

The figure below show the difference using both methods.

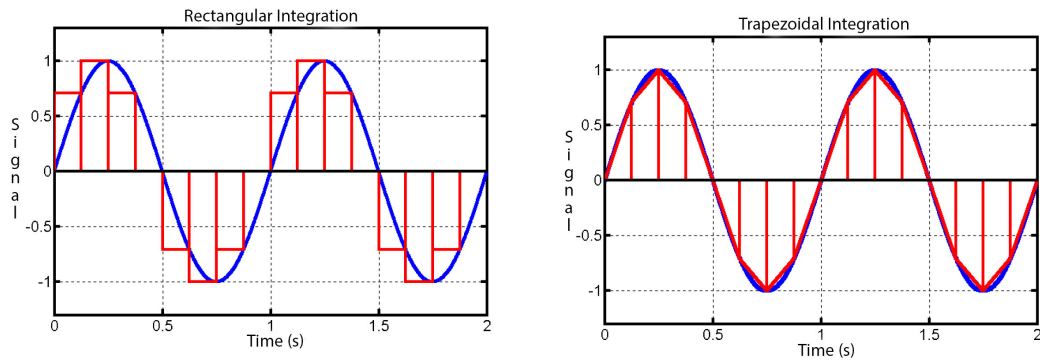
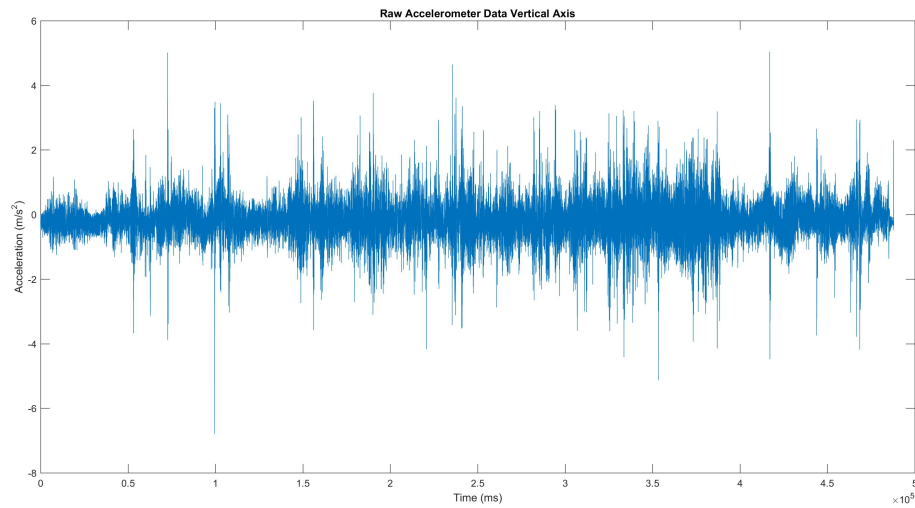


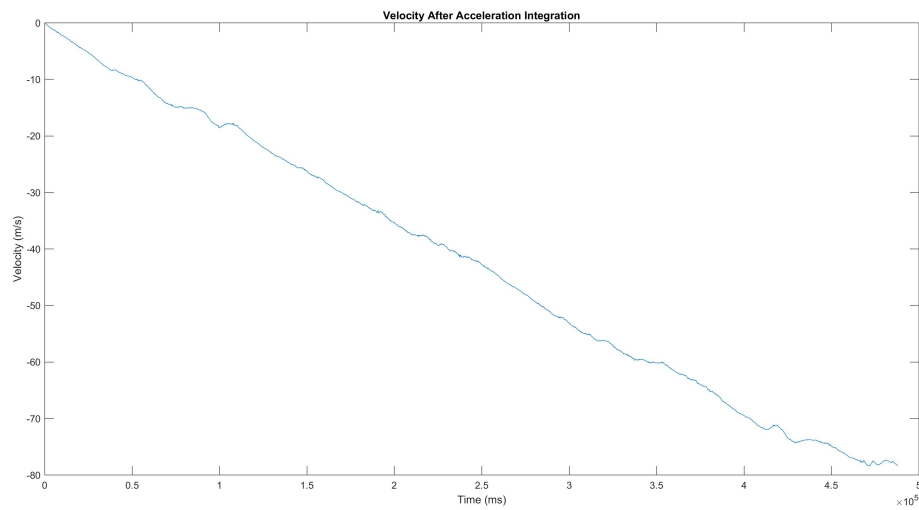
Figure 4.1: Integration using Rectangular (left) and Trapezoidal (right) methods of Sine Wave.

The integration was carried out using the trapezoidal method by the MATLAB suite. But without adequate cleaning of the signal, the result presents very error, caused by the drift and noise.

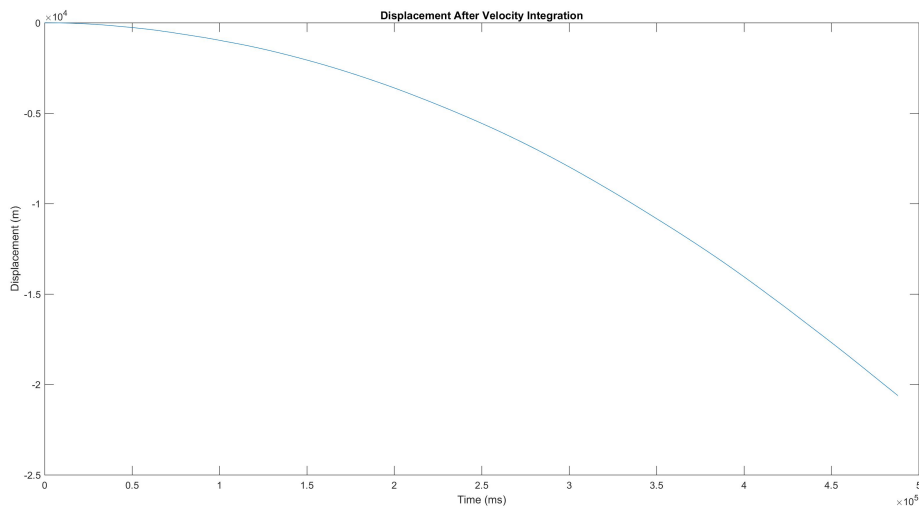
Various signal cleanup procedures will be discussed. The figure below shows the result of a raw signal integration using trapezoidal method.



(a) Acceleration



(b) Velocity



(c) Displacement

Figure 4.2: The result of double integration of a Raw Signal

As is possible see, the result is not realistic, considering it is vertical acceleration, so it is necessary to perform various steps to fix and clean the signal. First of all, the signal reorientation will be carried out respect the axes of the vehicle, and subsequently, various filter operations to clean the signal.

4.1 Accelerometer Reorientation

The Cartesian reference system of the phone must be aligned with the vehicle reference system, to detect the vehicle motion correctly. As shown in the figure below.

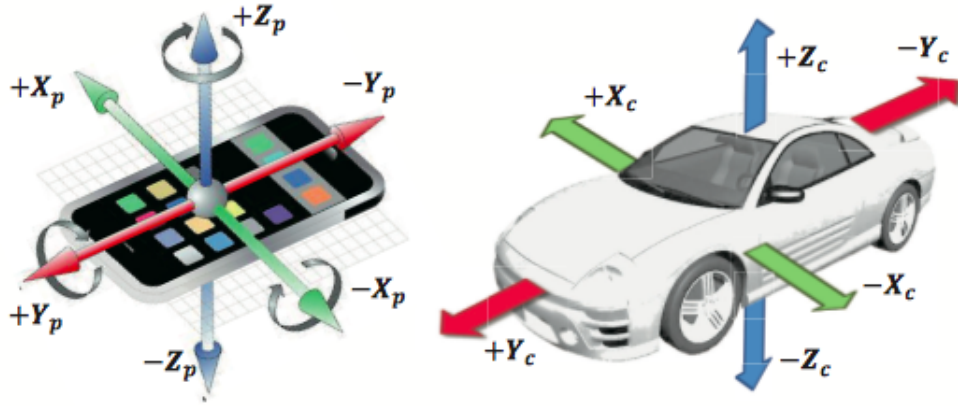


Figure 4.3: Correct alignment of smartphone respect to the vehicle cartesian frame.

Smartphone accelerometer detects the following accelerations: a_{x_p} , a_{y_p} and a_{z_p} . To determine the accelerations felt by the vehicle and locate road surface anomalies. The accelerometer must detect what happens in the direction perpendicular (Z axes) to the vehicle [14]. Respectively the X_p axis identifies the longitudinal direction, Y_p axis the transverse direction and Z_p the perpendicular direction respect to the xy plane.

To detect road anomalies, the direction of the z -axis must correspond to the direction of the z axis. If this condition subsists, the accelerometer is well oriented, contrarily it is not well oriented and needs to be reoriented. But even if starting from a precise orientation condition, during travel the phone may be moving, or due to unexpected vehicle movements, travel of climbing, downhill, curve, all of these causes could affect the misalignment of the smartphone frame respect to the vehicle frame.

The reorientation can be performed by the Euler Angles. Three angles that allow to defining the orientation in space of any body through a succession of elementary rotations.[7] The XYZ sequence was defined, a rotation around the x axis by an angle α (roll angle), one around the y axis by β (pitch angle) and one around the z axis by γ (yaw angle).

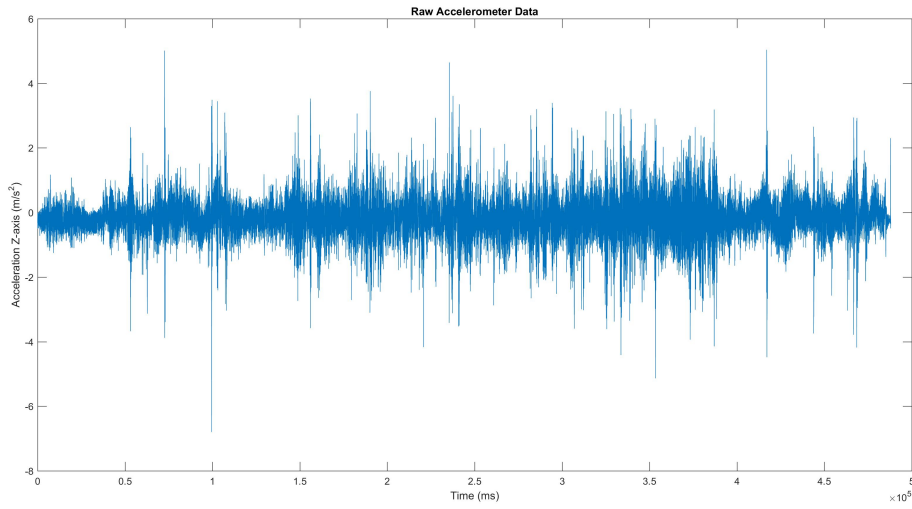
The equations that allows to reoriented data by the α , β , γ , angle are:[4]

$$a_{x_{reor}} = \cos(\beta)a_{x_p} + \sin(\beta) \sin(\alpha)a_{y_p} + \cos(\alpha) \sin(\beta)a_{z_p} \quad (4.3)$$

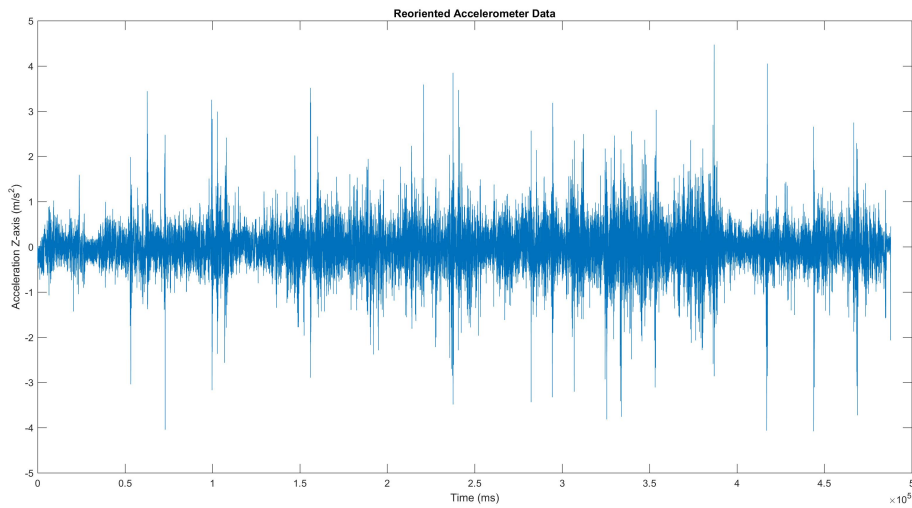
$$a_{y_{reor}} = \cos(\alpha)a_{y_p} - \sin(\alpha)a_{z_p} \quad (4.4)$$

$$a_{z_{reor}} = -\sin(\beta)a_{x_p} + \cos(\beta) \sin(\alpha)a_{y_p} + \cos(\beta) \cos(\alpha)a_{z_p} \quad (4.5)$$

The figure below, show an example of reoriented data.



(a) Raw



(b) Reoriented

Figure 4.4: The result of reorientation of raw data

Acknowledgments

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