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UNIVERSITAT POLITÈCNICA DE CATALUNYA

PROJECTE DE FI DE CARRERA

TÍTOL DEL PFC: Disseny d'un sistema d'estabilització de càmeres de baix cost mitjançant la implementació d'un "Gimbal analític"

TITULACIÓ: Enginyeria de Telecomunicació (segon cicle)

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Resum

L'estabilització de seqüències d'imatges o vídeo és important en diferent tipus d'aplicacions com la cerca de persones o l'inspecció de línees elèctriques. Qualsevol moviment implica un canvi en l'orientació de la càmera, requerint de rectificacions, a vegades complexes, d'imatge (com per exemple, un canvi de perspectiva). Es poden destacar dues solucions totalment oposades. Per una banda, s'han desenvolupat plataformes complexes amb sensor inercials i actuadors mecànics que estabilitzen contínuament la càmera (anomenats *gimbals*). Aquests sistemes acostumen a ser grans, pesats i cars. Per altra banda, hi ha una gran varietat de programaris, que per mitjà, exclusivament, del processat d'imatges permeten estabilitzar-les. Aquests programaris acostumen a requerir d'un elevat temps de processat i de potents ordinadors degut a la gran quantitat de dades que representa cada imatge. El projecte presenta la possibilitat de fer servir uns sensors inercials (a vegades ja presents, como en un UAV) però sense actuar sobre el moviment de la càmera. Les imatges son processades i estabilitzades fent servir les dades obtingudes pels sensors inercials.

L'objectiu d'aquest projecte és dissenyar i implementar un sistema gimbal analític d'estabilització de baix cost. El nou sistema utilitza una càmera digital de consum i una unitat amb sensors inercials (IMU), ambdós productes de baix cost comparats amb les solucions actuals. Un ordinador petit i de baix cost s'encarrega del control del sistema i es rectifiquen les imatges per mitjà del processat de les dades obtingudes pels sensors inercials (pero això es una sol·lució analítica, a diferencia de les solucions on la rectificació fa servir tècniques de processat d'imatges o actuadors). S'aconsegueix reduir significativament els recursos requerits per al seu processat i alhora evitar els complexos sistemes d'actuadors mecànics. Les tasques principals a realitzar han sigut el disseny e implementació del hardware i software necessari per a l'adquisició de les dades i posterior estabilització de les imatges. Per a que tot el sistema funcioni correctament, esdevé clau el sincronisme de les dades entre la càmera i la IMU (per això s'ha desenvolupat una estratègia per a garantir els sincronisme de les dades). Posteriorment, s'han estudiat e implementat diferents algoritmes d'orientació i rectificació d'imatges, continuant amb la verificació i validació del sistema. Finalment, s'inclouen les conclusions del treball i algunes futures millores o possibles aplicacions.

Title: Low cost camera stabilization system by implementing an analytical gimbal.

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Date: October, 29th 2012

Overview

Image stabilization of photos or video is important on different applications such as search-and-rescue or electrical power line inspection. Any motion creates a change on camera orientation, which can be balanced using complex image algorithms (perspective change, resizing, etc.).

Nowadays, two opposite options have been applied. The first one, uses a complex platform with sensors and actuators that are able to, in real-time, correct non-desired motions and vibrations or aim to a specific target. They are called gimbals. They are expensive, big and heavy. The second one, uses image processing techniques (such as pattern recognition algorithms), that are able to process images until an image stabilization effect is obtained. This software approach requires powerful computers, because of the big amount of data from each frame or image. The approach presented in this project, uses an inertial sensor (IMU) connected to a CPU. It is able to, in real-time, record inertial data and in parallel, or in post-processing, correct images using this data (analytical solution). A commercial camera is used. The entire system is controlled by the CPU.

Therefore, the main purpose of the project is the design, implementation and verification of a low cost image stabilization system by implementing an analytical gimbal. The system is composed by a small and portable computer responsible of image acquisition control and synchronism. Image stabilization is done in post-processing, reducing execution time considerably if compared with image processing techniques previously commented. It works with a low cost commercial camera and a low cost IMU, reducing overall cost. To work properly, it is critical a synchronism between data and image acquisition. The system performance is verified and validated on different scenarios. Finally, the results obtained and some future improvements or possible applications are presented.

Dedicated to all IG members,
specially to Eduard Angelats,
and to my family.

Dedicat a tots els membres de l'IG,
especialment a l'Eduard Angelats,
i a la meva familia.

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1. Introduction

1.1. Project scope

After years of study at the Polytechnic University of Catalonia, having finished previously a Technical Engineering on Telecommunications, the moment to do the project for Telecommunications engineering and Master has arrived.

This project is realized through collaboration with the Institut of Geomatics (IG, [1]) and more in particular, with the GIN[1] group. IG focuses on the promotion and development of Geomatics, through applied research and teaching. Some of sciences and technologies implied are the study, acquisition, and analysis of geographically-referenced spatial information. Geomatic disciplines include, among others, cartography, remote sensing, sensor calibration and orientation and geomatic engineering ([2], [3]). Meanwhile, GIN group is focused on research and integration of any available sensor for local geodetic applications, both in their geometric and physical aspects.

The main purpose of the project is the design, implementation and verification of a low cost image stabilization system implementing an analytical gimbal. The system is composed by a small and portable computer responsible of image acquisition control and synchronism. Image stabilization is done on post-processing, reducing execution time considerably if compared with other solutions. It works with a low cost commercial camera and a low cost IMU, reducing overall cost. To work properly, it is critical a synchronism between data and image acquisition. The system performance is verified and validated on different scenarios.

1.2. Goals

The main goals of this project are:

- Design and implementation of the required hardware and software to control image acquisition and record sensors data.
- Design and implement synchronization algorithms (camera and IMU).
- Study of orientation and image rectification algorithms.
- Design and implement orientation and rectification algorithms.
- System validation and verification.

[1] Integrated Geodesy and Navigation

1.3. Document overview

This document follows the project development steps. Beginning from the state of the art and main platform elements (CPU, camera, sensors ...) to a global system view, evaluating its performance.

Chapter 2 explores the state-of-the-art about image stabilization techniques and procedures, exposing some solutions.

Chapter 3 offers a general view about the system design as well as its main blocks, elements and interfaces.

Chapter 4 specifies the system development procedure giving detailed information about system elements configuration and connection.

Chapter 5 is focused on data processing and different algorithms implemented.

Chapter 6 presents the tests carried out to validate the system performance as well as the obtained results.

Chapter 7 summarizes project conclusions and presents an future improvements and possible applications.

2. State of the art

As soon as analog images started to be recorded, it was noticed that any motion during exposition time for single frame or a sequence of images, may result in a poor image quality (as blurring does).

Therefore, different techniques to compensate non-desired motion have appeared across the time, as gimbals (hardware system) or image processing (software). To reduce blurring or vibrations associated with the motion of a camera during sensor exposure time or between different photos, image may be compensated for pan, tilt and roll (the three rotational axes) of a camera. Moreover, a size adjustment or perspective modification may be required, depending on stabilization quality level.

An only-hardware technique is the lens-based systems or gimbals (Fig. 2.1). These systems started to work at fifties. But their main constraints are cost and size. Some examples of actual gimbal systems can be found on Internet [4].

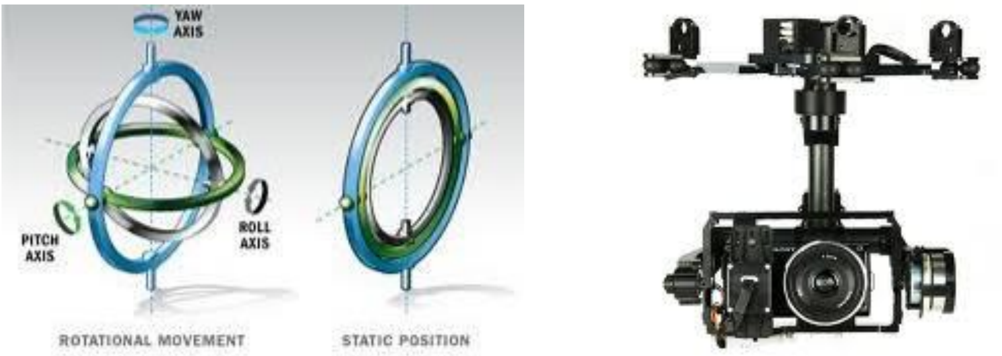


Fig. 2.1. Gimbal representations

In the particular case of commercial cameras, different image stabilization techniques [5] appeared depending on manufacturers guidelines. Image stabilization helps to steady the image projected back into the camera by the use of a "floating" optical element—often connected to a fast spinning gyroscope—which helps to compensate for high frequency vibration (hand shake for example) at these long focal lengths.

As an example, Canon EF SLR uses lenses with image stabilization while Nikon named it as VR "Vibration Reduction" (Fig. 2.2). Both systems stabilize images from hand-holding [6] effects. It helps to replace a tripod for making sharp photos and both can be defined as hardware compensation techniques.

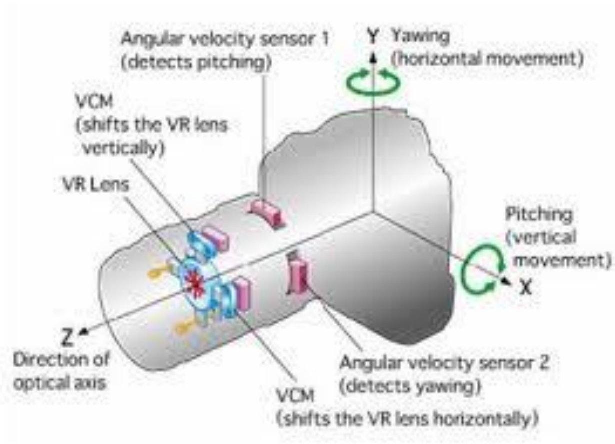


Fig. 2.2. VR example

An only-software technique is the digital stabilization [7]. These systems are newer than hardware ones, because of the big amount of memory and processing speed required to work with images, particularly if it is intended to work at real time. One common solution is look for points of interest and calculate their relative pixel displacement from frame to frame. An example of software able to do that is *virtualdub* [8], which is open source software able to stabilize a sequence of images [9].

But there are other different techniques [10] possible. An example is optical stabilization ([11] and [12]). These techniques are used to stabilize the recorded image by varying the optical path to the sensor, shifting the electronic image from frame to frame of a video enough to counteract the motion or lens-based, as explained before, for Nikon and Canon commercial cameras.

Therefore, two ways are well defined, through a hardware implementation or software image processing. Only a few times, both are connected, being this the case of study of the project. Specially, if the system (maybe an UAV), has an IMU unit for navigation. Then, its data can be used for image stabilization too.

It has been found an example similar to project proposal, but working on a different way. It uses gyroscopes and accelerometers to estimate the blur effect due the camera's acceleration and angular velocity during and exposure. Camera motion blur is one of the most common reasons for discarding a photograph. If the blur function is known, the image can be improved by deblurring it with the obtained function [13].

3. System architecture

3.1. Overview

The system main elements are:

- Camera.
- CPU (system controller).
- IMU (inertial sensors).

Two of them are reused from GIN group (CPU and IMU). While the camera, must be selected as a part of the project research (section 4.1.2).

The system is mounted on a single platform where all elements are fixed to the platform in order to reduce possible vibrations or malfunctioning through its life cycle. The platform can be mounted on different vehicles such as a car, a copter or an airplane.

3.2. Hardware architecture

To synthesize, the system main blocks, are represented in Fig. 3.1. IMU is connected to a CPU (bidirectional communication). It is logged inertial data from sensors. Then, this data is processed in order to obtain image rotations and displacements. A battery feeds the CPU and the IMU (the camera has its own battery).

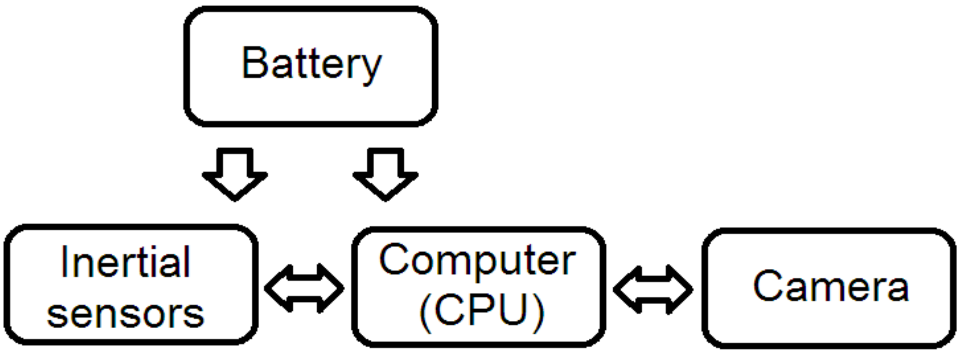


Fig. 3.1. Main system elements

The battery is used to develop an autonomous system (as for outer test as a power supply source). In addition, to feed each element with its correct level voltage, it is required some logic level converters (as example, from battery 12 volt to CPU 5 volt and IMU 3.3 volt inputs).

Inertial data is obtained from the IMU unit, connected directly to the main controller (CPU) by a SPI port. For the project it is proposed to work with a high performance MEMS[2] IMU. This project allows study the feasibility of using this IMU instead of using more expensive and high performance IMUs (as explained in section 4.2).

For the camera, a market research is critical to observe technological differences from each manufacturer or model. Cameras features are important to decide for the one that fits better for the project purposes. Some important features are:

- Sensor size and resolution.
- Price.
- Infrareds (IR), or any kind of external shutter release control.
- Synchronism speed.

3.3. Software architecture

The software architecture can be divided into four groups (Fig. 3.2). Image acquisition is responsible of all the processes to control remotely the camera to take a photo. Synchronism is critical to have a timestamp on inertial data and photos to relate them. Data processing works with raw data from inertial sensors (IMU). After processing this data, it is stored on a file. This file is used by image processing to stabilize images.

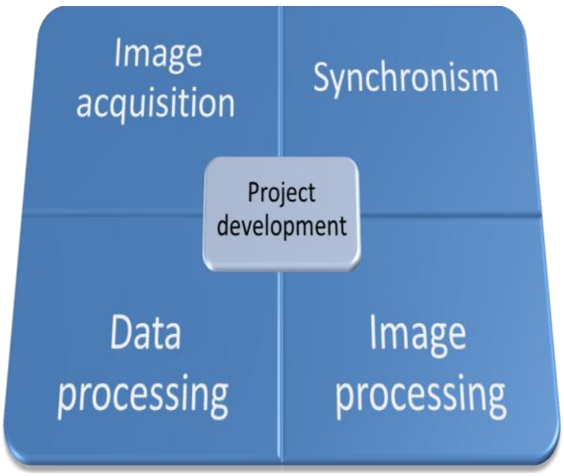


Fig. 3.2. Project group division

To control the system is used a flexible and open board as Overo (CPU), from Gumstix [14]. It is a computer-on-module system (ARM architecture) implementing Linux as operative system (Angstrom distribution). Linux is selected as operative system due to flexibility and complete control of software and hardware that provides.

[2] Micro-Electro-Mechanical Systems

Overo is responsible of (Fig. 3.3. System overview)

- Generating camera shutter release signal (1).
- Detecting camera flash trigger signal (2).
- Stablishing a communication link to the IMU (3).
- Logging inertial data, flash events, control info and timings (4).

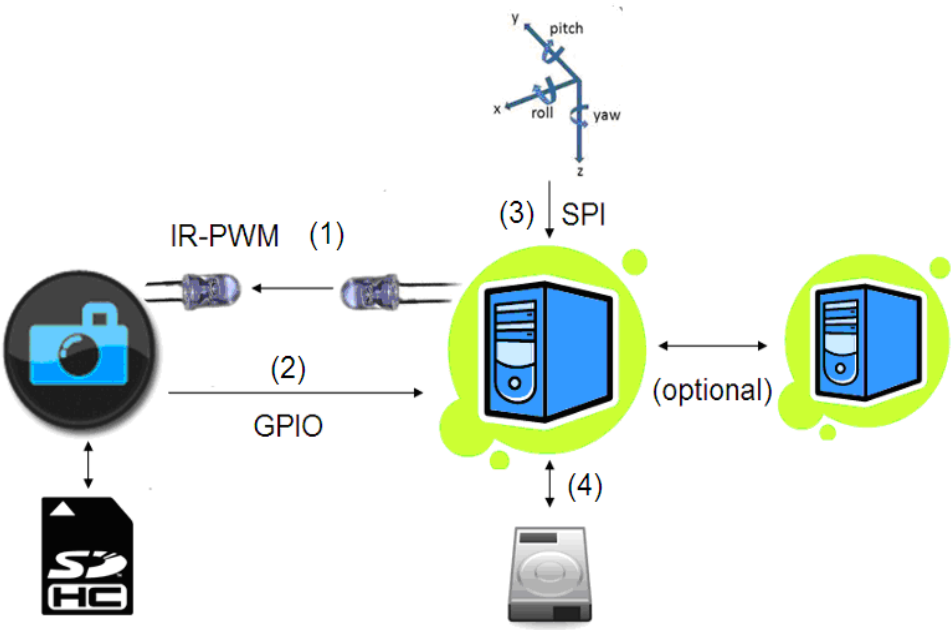


Fig. 3.3. System overview

All these elements are detailed in next chapter.

4. Detailed system design

4.1. Camera

4.1.1. Introduction

Generally, consumer grade cameras can be divided into two groups:

- Reflex.
- Compact.

Reflex cameras are considerably bigger and they have a big variety of available interchangeable lenses. They have a mirror inside the camera body resulting in a more fragile and expensive system but offering the best results. While, compact camera bodies are smaller, cheaper and without interchangeable lenses. It makes them more robust but not as good as Reflex.

Lately, a new concept is appearing mixing the strengths from both types. They are called EVIL or MILC (Mirrorless Interchangeable Lenses Camera) cameras. Their main advantages are a reduced price compared to Reflex due to the internal mirror being removed and a body size similar to compact ones. But they work with interchangeable lenses too. Its price is between both types (from 400 to 800 €).

4.1.2. MILC Cameras

There are plenty of manufacturers offering at least one model of EVIL cameras as SONY, PENTAX, RICOH or OLYMPUS. They have many different specifications and features, as some have lower prices and others have new designs and better features (sensor size or resolution).

In comparison to industrial grade cameras, used a lot for computer vision applications, they have not a SDK[3]. It results on a more difficult software integration and camera control. However, the cost is much lower.

The present available cameras specifications are shown in Table 4.1 and Table 4.2. There are a lot of different criteria to take into account such as:

- Sensor size and resolution.
- Price.
- Weight and body size.
- Photo and video format.
- Flash synchronism and flash connector type.

[3] SDK: Software Development Kit

- Outputs as HDMI, AV, …
- Lens mount type & Adapters required.
- Shutter speed and a shutter remote control option.
- Frames per seconds (FPS) with and without flash.

Table 4.1. Cameras comparison

Manufacturer	Model	Sensor (mm)	Res (Mpx)	Price (€)
PANASONIC	DMC-GX1X	17,3 x 13,0	16	800
NIKON	V1	13,2 x 8,8	10,1	600
PENTAX	K-01	23,7 x 15,7	16,28	640
OLYMPUS	EP-3	17,3 x 13	12,3	800
OLYMPUS	E-PM1	17,3 x 13	12,3	500
OLYMPUS	E-M5	17,3 x 13	16,1	900
FUJIFILM	X-Pro1	23.6 x 15.6	16,1	1400
SONY	NEX-5N	23,5 x 15,6	16,1	600
SONY	NEX-C3K	23,4 x 15,6	16	600
SONY	NEX-7	23,5 x 15,6	24,3	1000
RICOH	GXR	23.6 x 15.7	13	1000

Table 4.2. Cameras shutter, flash and format info

Manufacturer	Model	Flash sync (s)	Video
PANASONIC	DMC-GX1X	1/160	Full HD: 1920 x1080
NIKON	V1	1/250; 1/60	HD: 1920 x 1080/60i (H.264/MPEG-4)
PENTAX	K-01	1/180 & HSS[4]	MP4 (H.264)
OLYMPUS	E-PM1	1/60 & 1/160	AVCHD, AVI
OLYMPUS	EP-3	1/180	AVCHD; mp4 (H.264)
OLYMPUS	E-M5	1/250; 1/180	Full HD: 1920 x 1080
FUJIFILM	X-Pro1	1/160; 1/180	H.264
SONY	NEX-7	1/160	AVCHD; mp4 (H.264)
SONY	NEX-5N	1/160	AVCHD; mp4 (H.264)
SONY	NEX-C3K	1/160	MP4 (H.264)
RICOH	GXR	1/60	MP4 (H.264)

For the project the main characteristics to take into account are sensor size, resolution, body size, fps with flash, flash synchronism speed, an external shutter release control (such as infrareds or USB) and digital and analog outputs for a price adjusted to market.

[4] High Speed Sync: HSS

Main strengths and weaknesses of each model are resumed in Table 4.3 (green = good, yellow = indifferent, red = bad). Also, some of the cameras are shown in Fig. 4.1.

Table 4.3. Some strengths and weaknesses of each camera.

PANASONIC	NIKON	FUJIFILM	SONY	OLYMPUS
DMC-GX1X	V1	X-Pro1	NEX-7	E-M5
460 €	13,2 x 8,8 mm	23.6 x 15.6 mm	LANC	Eye-Fi (Wi-Fi)
Full HD	10,1 mpx	1.400 €	Linux (S.C.)	Bluetooth
N/A fps	AV output		24,3 mpx	
	1/60 (Sync.)		10 fps	
	Flash con.		>1000 €	
OLYMPUS	SONY	SONY	PENTAX	OLYMPUS
E-PM1	NEX-3	NEX-5	K-01	EP-3
Eye-Fi (Wi-Fi)	Eye-Fi (Wi-Fi)	IR	HSS	SDK Reflex only
No IR (USB-jack)	No IR	Linux (S.C.)	AV	
400 €	600-700 €	Flash con.	1 fps (RAW)	
		Eye-Fi	600 €	

Fig. 4.1. Evaluated models (Panasonic, Sony, Nikon and Pentax)

Finally, it is decided to buy SONY NEX-5N (newest model) due its good sensor size and resolution, body size and weight, IR control feature, Eye-Fi available [15]. It is currently used by several photogrammetric applications [16]. Its main constraint is the particular flash connector, not common (not a “foot shoe”). Due this, it is required to take flash signal accurately from a small flash pin.

4.1.3. Sony NEX-5N

Sony NEX-5N is the selected camera (Fig. 4.2). On one hand, it has a small body compared to other options. It has a good sensor resolution, an HDMI output and it is relatively light. On the other hand, it have been found adapters for the camera lenses type, allowing the group to reuse other lenses available from other cameras or reuse Sony's lenses for the others one.

Fig. 4.2. Sony NEX-5N front view.

Furthermore, it has an IR interface, making possible an external shutter release control without opening the camera body or soldering it. However, its flash connector is not and standard one, and adapters are expensive (around 100 €) making it a weak point. This is important because photographs are time referenced to the flash pulse event. It is fixed carefully a cable on the flash device.

The camera has been bought by 700 € and includes two lenses (18-55 and 35 millimeters). To sum up, Sony's main features are [17]:

- 16.1 megapixels.
- CMOS sensor, RGB.
- 23,5 x 15,6mm.
- Full HD AVCHD.
- 10 fps maximum.
- E type lens mount.
- ISO 100 - 25.600.
- Flash synchronism up to 1/160.
- IR interface.
- RAW, RAW + JPEG, JPEG.
- HDMI and USB.
- 201 grams and 110.8x58.8x38.2mm.

Further details can be found in Annexes 9.1.

4.2. IMU

IMU stands for *Inertial Measurement Unit.* Processing its raw data, it is possible to obtain system motion in order to use it later for image stabilization [18]. It is an electronic device, commonly used on mobile devices as aircraft. It is composed by an ISA unit plus the needed electronics and communication systems to provide data (usually timers, angular rates and linear accelerations, see Fig. 4.4). An ISA unit is a device composed by one clock, several angular rate sensors or gyroscopes (usually 3), several accelerometers (usually 3) and a mechanical holding structure ([19] and [20]).

An INS (Inertial Navigation System) is an IMU plus a processor. They are usually connected to a GPS and used for navigation.

From accelerometers measurements it is possible to obtain velocity or displacement:

$$a = \frac{dv}{dt} \approx \frac{\Delta v}{\Delta t}$$

From gyroscopes measurements it is possible to obtain the three axis rotations:

$$\omega = \frac{d\theta}{dt} \approx \frac{\Delta \theta}{\Delta t}$$

Rotation angles [21] are defined in Fig. 4.3:

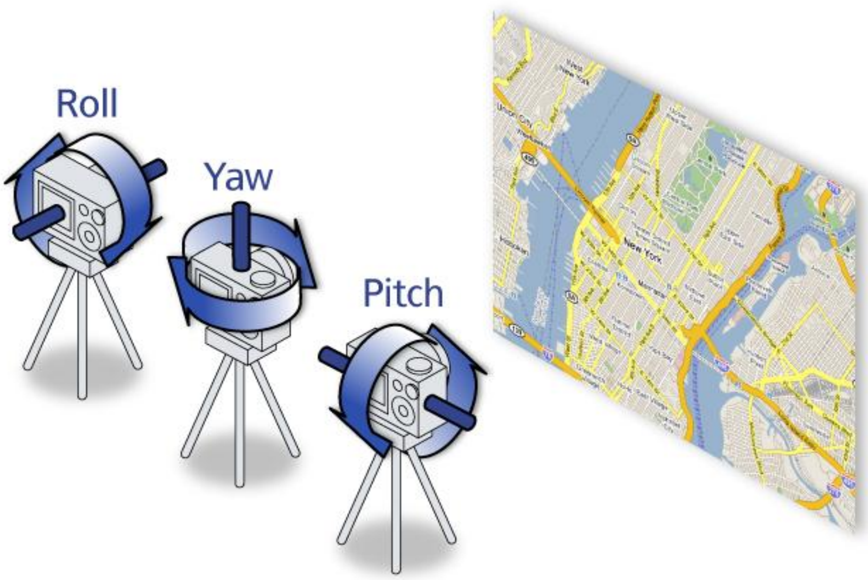


Fig. 4.3. Roll, yaw and pitch definitions

In this project, IMU is going to report camera motion. It is important to place IMU as close as possible to camera sensor and both must become moving on solidarity.

But IMUs are not perfect systems and they are affected by some errors. The errors ([19] and [22]) affecting and IMU signal basically are: scale factors, bias, misalignments, white noise and quantization noise.

IMUs can be classified depending on sensors technology, cost and performance. On top performance, they use optical sensors (navigation and tactical) while at low levels (low cost) is common to work with MEMS sensors [23]. Hence, they can be classified as:

- Navigation grade.
- Tactical grade.
- Automotive grade (low cost).

A common configuration for an IMU unit is shown in Fig. 4.4.

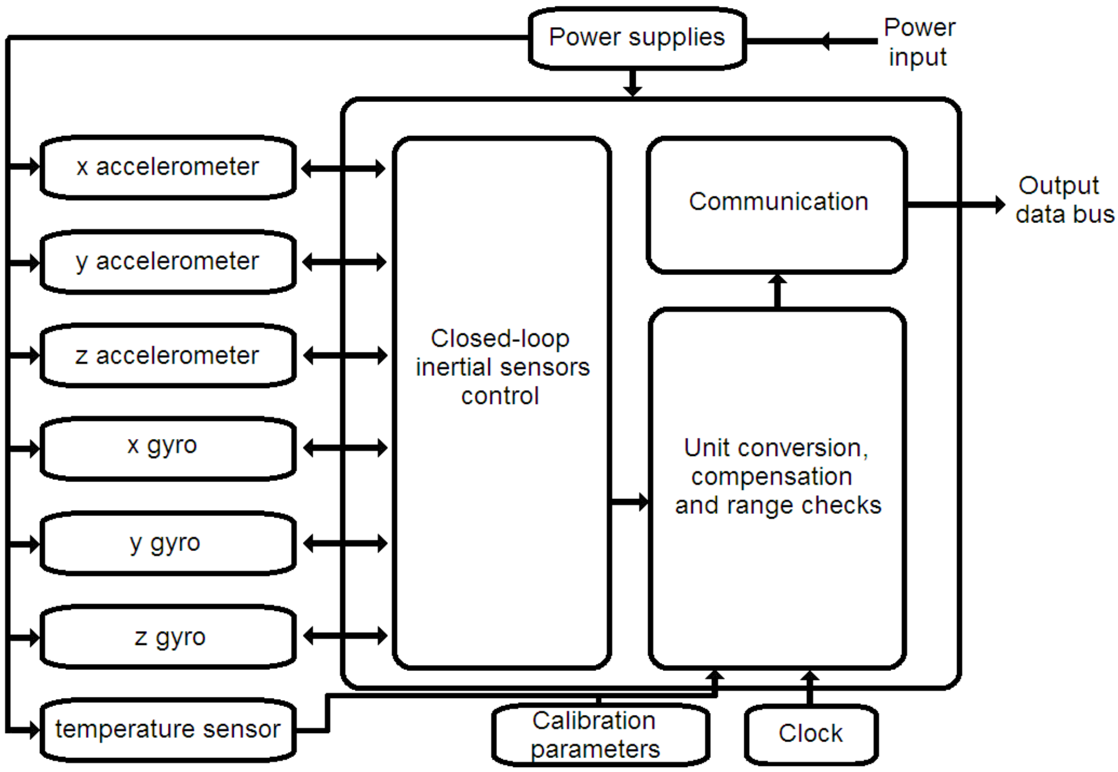


Fig. 4.4. IMU blocks

INS/GNSS hybridization [22] reduces system weaknesses of each element as drifts for the IMU or loss of signal for the GPS.

4.2.1. ADIS16488

The selected IMU is ADIS16488 from Analog Devices. It has been selected because of its price, size and weight. The manufacturer defined it as a complete inertial system that includes a triaxis gyroscope, a triaxis accelerometer, a triaxis magnetometer and a pressure sensor [24]. It is considered as a low cost tactical grade IMU.

Each inertial sensor in the ADIS16488 combines industry-leading MEMS technology with signal conditioning that optimizes dynamic performance (Fig. 4.5).

Main features and specifications:

- Triaxial, digital gyroscope with digital range scaling
  - ±450°/sec dynamic range
  - <0.05° orthogonal alignment
  - ~6°/hr in-run bias stability
  - 0.3°/√hr angular random walk
  - 0.01% nonlinearity
- Triaxial, digital accelerometer, ±18 g
- Triaxial, delta-angle and delta velocity outputs
- Triaxial, digital magnetometer, ±2.5 gauss
- Digital pressure sensor, 300 mbar to 1100 mbar
- SPI
- Typical Bandwidth (kHz): 0.33kHz
- Noise Density (°/s/rtHz): 0.0050
- Supply Current : 254mA

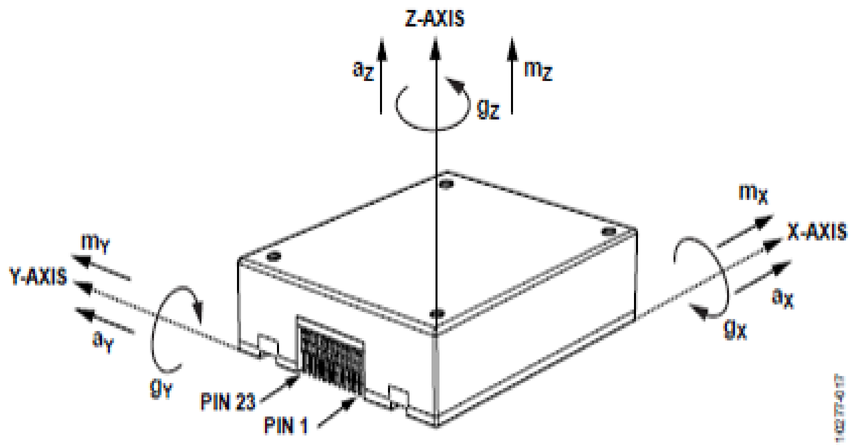


Fig. 4.5. ADIS axis orientation

The project brings the opportunity to evaluate the performance of this new technology on an application where higher IMUs grade are typically used.

More details in Annexes 9.2.

4.3. CPU: Gumstix

Gumstix, represented in Fig. 4.6, is defined as small open source hardware. A user can download and work immediately with an O.S. image offered by manufacturers. A variety of products are offered such as:

- Computer-on-module (Overo and Verdex Pro).
- Expansion boards
- Gumstix packs.
- Gumstix computers.

Fig. 4.6. Gumstix Overo FIRE

Overo is one type of computer-on-module developed by Gumstix (the other type is the Verdex series). There are a lot of versions but the one selected is Overo Fire COM. This provides a powerful solution implementing wireless communication and a CPU+DSP by around 200 € (2012). It has a tiny, OMAP3530 computer-on-module based on an ARM Cortex-A8 with DSP capabilities and 3D graphics acceleration. Its small size is perfect for the project purposes, being able to be mounted on a small platform. It has 802.11b/g (Wi-Fi) and bluetooth communications on-board.

It works with an Angstrom (Linux) distribution with no visual environment (reducing image size and load time and increasing execution speed). Overo mains specifications are [25]:

- Architecture ARM Cortex-A8.
- Processor on COM Texas Instruments OMAP 3530.
- Processor Speed 720 MHz.
- Digital signal processor (DSP) C64x+ digital signal processor (DSP) core OpenGL for 2D and 3D graphics acceleration.
- RAM 512 MB.
- NAND 512 MB.
- Bluetooth and 802.11 b/g included
- microSD card slot.

This board is small but powerful enough to control and operate the overall system.

But it is necessary an expansion board for console programming/operation. IG has a Chesnut43 [26] development board. It is ideal for laboratory tests, due its huge amount of connections (Audio, Ethernet, 40 pin header and USB). But, it is one of the largest and heavy modules (next, a smaller and simpler solution is available). Chesnut43 board (Fig. 4.7) main interfaces are:

- LCD Touchscreen.
- Ethernet.
- Console terminal (USB).
- Stereo Audio.

Fig. 4.7. Chesnut43

There are other modules available. To have a more portable option, it is decided to buy and test a *Pinto TH* (Fig. 4.8). It is considerably smaller than the previous one (due it has less connection interfaces available). It has only a 60 pin connector but its size is close to the Overo one. It makes it ideal for low size equipment. It can communicate by serial port or Wi-Fi to a development computer (while Chesnut uses Ethernet and a dedicated console port).

Fig. 4.8. Pinto TH board

Should be mentioned, that simpler and cheaper solutions (such as *Arduino*[5]), are discarded. Its low frequency clock will result on a probable poor timing accuracy. Moreover, its processor may overload too (as more functionalities are included).

[5] www.arduino.cc

4.3.1. CPU Interfaces

From module available hardware, there are some modules of important consideration and others for future implementations or improvements.

The necessary interfaces are:

- Pulse Wavelength Multiplexing (PWM).
- GPIO (Digital inputs/outputs).
- Infrared (IR).
- Serial Protocol Interface (SPI).
- Clock (internal or external)

SPI is used for IMU communication and, in a near future, to implement a virtual SD memory for the camera (capturing images for real-time processing). The IR control signal for camera shutter release is generated by a PWM port.

While, GPIO pin captures flash trigger from the camera. Clock is critical to be used as a time reference to relate images and IMU data.

Some future implementations could use also Wi-Fi or Bluetooth for system monitoring, data acquisition, data transmission, etc…

4.3.2. Time synchronism

The time synchronism is crucial to relate inertial data from sensors and photographs. Some of the previous interfaces are used for synchronism. This is the case of:

- PWM (IR pulse generation).
- GPIO (flash trigger detection).

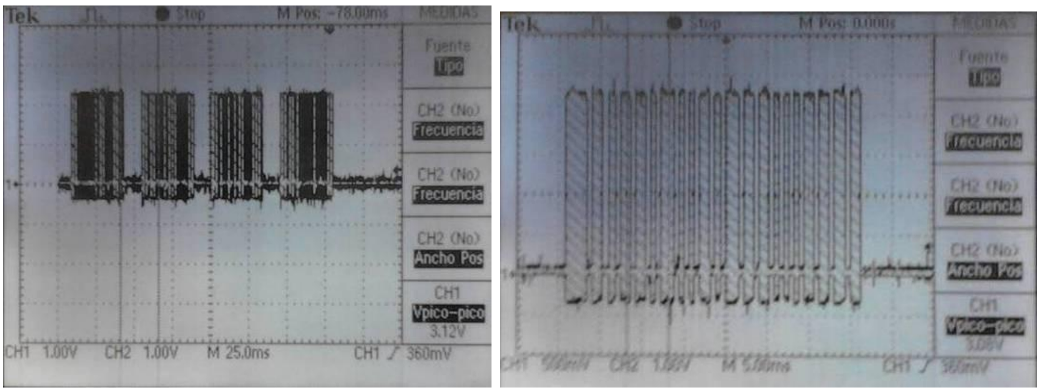


Fig. 4.9. PWM signal printscreens

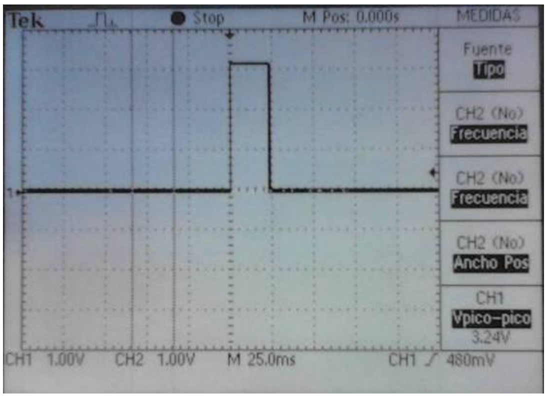


Fig. 4.10. Flash trigger signal printscreen

Therefore, a PWM signal of 38 kHz (Fig. 4.9) is connected to an IR emitter circuit (section 4.4.3).

The flash trigger signal (Fig. 4.10) is sent via the camera flash connector that is connected to an Overo GPIO input.

The flash pin out is resumed in Table 4.4. This strobe signal is used for image acquisition time reference.

Table 4.4. Flash pin out

Pin	Function
1	UNREG
2	CLK
3	SIO
4	GND
5	**STROBE** (flash trigger)
6	PGND
7	LOGIC_VDD
8	MIC_GND
9	MIC_L
10	MIC_C
11	MIC_R
12	GND
13	ID1
14	ID2

The flash trigger signal is measured as a 3.3 volt signal with a minimum period limited by the maximum available flash synchronism speed (1/160 seconds).

Thus, Overo is responsible of IR control (PWM) and flash detection (GPIO). More details about GPIO and PWM configurations in Annexes 9.4 and 9.5, respectively.

4.3.3. Environment set up

Environment set up is mandatory before to start working with the system. It is necessary to:

- Compile a Gumstix image with SPI enabled.
- Compile a PWM driver with the previous image.
- Load the image and the driver in Overo SD.

The system works through an operating system based on Linux, an Angstrom distribution (3.2. version).

An image can be obtained from the Gumstix webpage [27], and a guide to create a bootable SD can be found as well online [28]. A different PC is used for all these processes as a development PC (also working with Linux, but it works with *Ubuntu* 12.04 distribution).

Pre-built images offer some of the available features and hardware inputs/outputs. But for the project requirements, its own image is necessary (SPI is not working by default). Moreover, a driver must be compiled to work fast enough with the PWM. If not, the PWM on/off state changes will be too slow (few miliseconds), not being able to generate the correct signal.

So imperative is to have user permissions to *read&write* in all folders and files. It allows working correctly with the SD memory.

To compile the image and the driver, an Open Embedded Environment (OE) is required. This is installed on the development PC through a complex configuration process found on different web pages. There is the official one from Gumstix, [29], and a more generic one from OE platform [30] (it is recommended to follow the first one which is particularly explained for Overo).

It is important to follow the entire process as a not privileged user (not as a root). This is because OE compilation is so risky and it fails (to prevent operating system crash) if it is used as a root user (when $ symbol is present on a command, it means not to use a root user, while if # symbol is present, then it means to use a root user).

The OE function basis is detailed in Fig. 4.11. Basically, it downloads the main files (250 MB). Once installed, *bitbake* must be downloaded (but importantly not installed) and is used to download an omap3 console image with the command:

bitbake omap3-console-image

Mainly, OE downloads an image of the O.S (lot of Gb because of supplementary files required). Finally with this image, you are able to compile a new customized distribution or a driver (as PWM driver, explained below). All these processes require a lot of disk space and time.

Fig. 4.11. Driver compilation process

Furthermore, the PWM driver ([31] and [32]) is required as explained before to work fast enough with PWM configuration (frequency, duty cycle, on/off states …). Once it is compiled, a **.ko* file is generated by the OE environment that must be copied to Overo files system.

Now, system is correctly configured and provides the necessary interfaces to work with it. More details about PWM commands in Annexes 9.5.

4.3.4. Programming codes and cross-compiling

The software selected for code compiling is Eclipse. It is an open-platform based on Java but able to work with C and C++. Eclipse is installed on the development computer and it is used to compile the codes (which are going to be executed on Overo after). Files are transferred by an Ethernet link (Wi-Fi available too). How both computers are related is represented in Fig. 4.12.

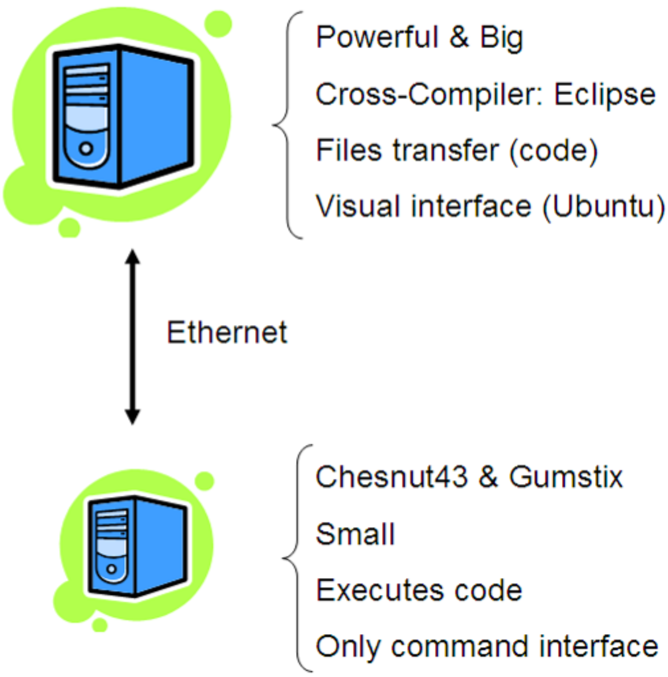


Fig. 4.12. Cross-compiling representation

Therefore, Eclipse must be correctly configured to work as a cross-compiler. It is required to download a compiler for C and C++ and they are generally named as GCC[6].

Once it is downloaded, a build solution must be configured relating to GCC files (Fig. 4.13)

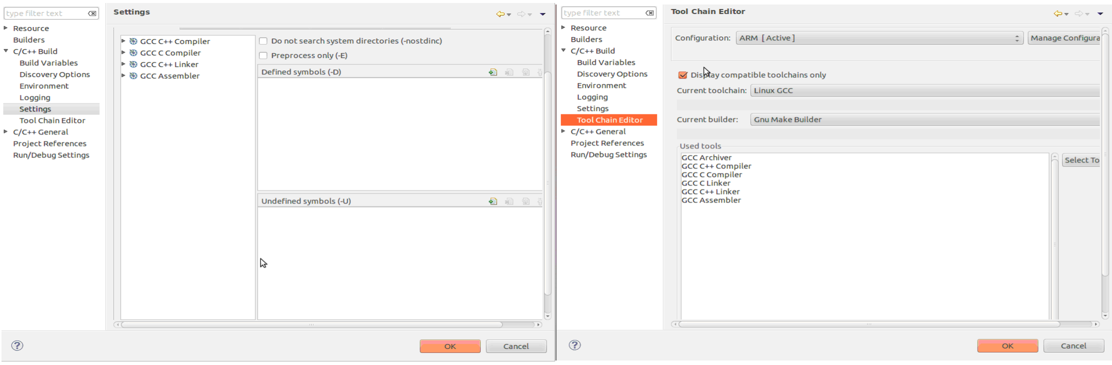


Fig. 4.13. Build configuration example

Thus, each time a program is compiled for Overo platform, user must only select the correct configuration.

4.3.5. Files transferring: Ethernet and Wi-Fi

As noticed before, Overo saves data files that must be processed later. Moreover, some files must be uploaded to Overo board. To do that, two available solutions are used.

The first solution is an Ethernet communication. Its high data rate is perfect for lab development with Chesnut43 development board.

The second solution is a Wi-Fi link. It is perfect for wireless situations, but it has a lower data rate (compared to Ethernet) and it has been found that doesn't work properly if Ethernet interface is enabled (doesn't mean connected).

Both configurations are detailed on Gumstix web page and wiki. A configuration file is loaded on computer boot:

/etc/network/interfaces.conf

6 http://gcc.gnu.org/

4.4. Communications interfaces

4.4.1. IR introduction

Infrareds (IR) are electromagnetic radiations and they are emitted or absorbed by molecules movements. They are defined on a part of the spectrum and occupy a small part of visible light spectrum too (Fig. 4.14). They include the thermal radiation produced by objects depending on its heating.

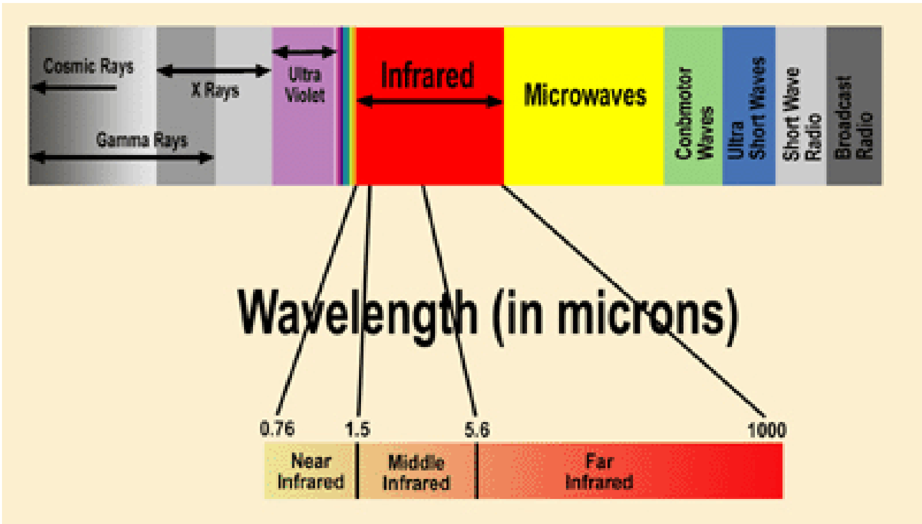


Fig. 4.14. Spectral division

Infrareds are commonly used on different areas applications as:

- Communications
- Night Vision
- Thermography
- Tracking
- Heating
- Climatology
- Astronomy

For this reason, they are selected as wireless communications system for camera shutter release control.

4.4.2. IR communications principles

As explained before, IR can be used as communications system. To begin, an IR diode, a controller and a resistor is enough to emit IR signals. An example circuit can be found on Fig. 4.15.

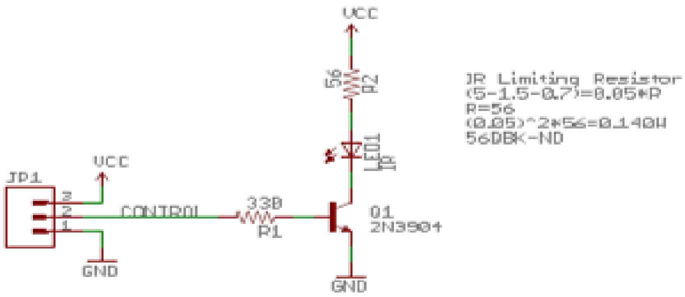


Fig. 4.15. Example IR scheme

In order to obtain a codified IR signal, zeros (0) and ones (1), a carrier signal is necessary. Typically, carriers are of some tens of kHz, as 38 or 40 kHz. The presence of the carrier stimulates IR diode to emit IR light, (1), while the absence is considered as a zero (0). Fig. 4.16 represents this sequence [33].

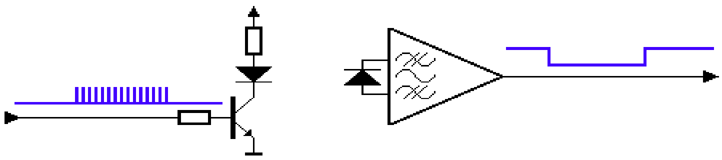


Fig. 4.16. IR scheme

4.4.3. Sony IR code: SIRC

But, not a single standard is used for all IR system. Therefore, it is necessary to discover how to communicate with this specific camera. It has been found that Sony NEX-5N camera uses a protocol known as SIRC (Sony Infrared Remote Control), [34].

The SIRC protocol main features are:

- 12-bit, 15-bit and 20-bit versions
- 5-bit for address and 7-bit fir command (12 bit)
- Pulse width modulation (PWM)
- Carrier frequency of 40kHz
- Bit time of 1.2ms or 0.6ms (Fig. 4.17)

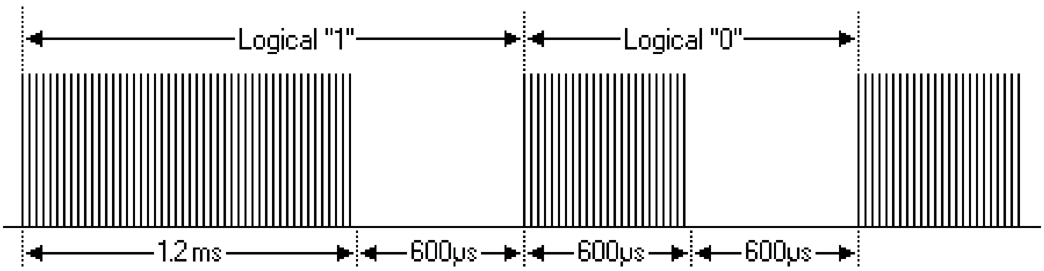


Fig. 4.17. IR logic representation

On Fig. 4.18, a code example is shown:

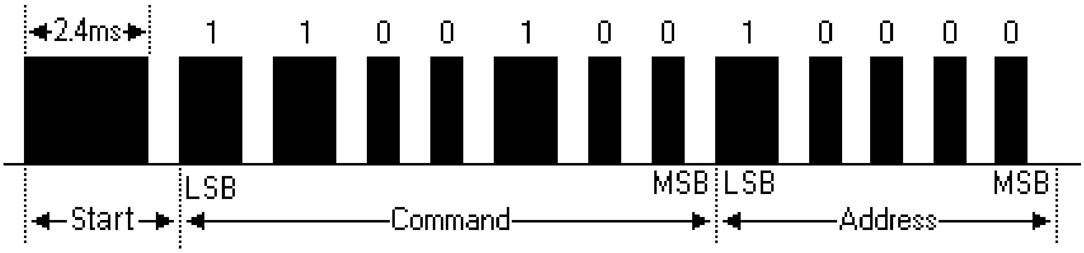


Fig. 4.18. IR sample code

It is decided to develop a specific code for the project (some example codes on [35], [36] and [37]). The code is able to take a photo, take a photo with 2 seconds delay and start/stop video acquisition. By now, only first one is used.

4.4.4. IR kit

Infrared systems are common and cheap. A small kit, Fig. 4.19, is ordered. Moreover, an IR receiver too (to verify IR emitter works if it fails to communicate to IR camera receiver). Kit [38] is composed by:

- IR diode emitter.
- Transistor.
- Resistors.
- PCB

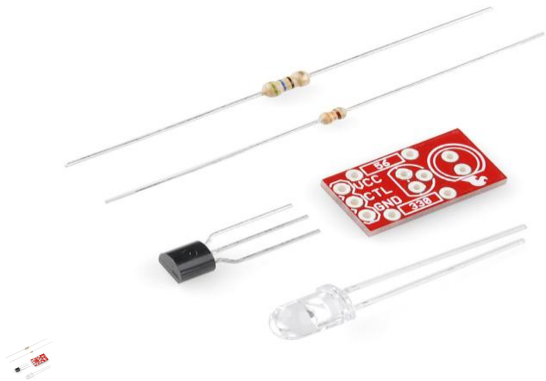


Fig. 4.19. IR transmission kit

It operates at 38 KHz band, 5 volt level and it has a low level current consumption (few mA). How to operate with IR can be easily found ([39], [40]). But, for this particular case it must match with Sony NEX-5N IR receiver.

As it seems to be easily implemented, and in order to understand and control in a deepest way the system, it is decided to implement one’s own. Other options are a SONY official remote control RMT-DSLR1 [41] and a cheapest model but unofficial [42].

4.4.5. SPI

SPI (*Serial Peripheral Interface)* communication is used for the communication link between the IMU (ADIS16488) and the Overo. It is a synchronous serial data link standard able to communicate at both directions at the same time (full-duplex, Fig. 4.20). Devices are defined as Master or Slave and multiple slave devices are allowed through a Chip Select (CS) pin [43].

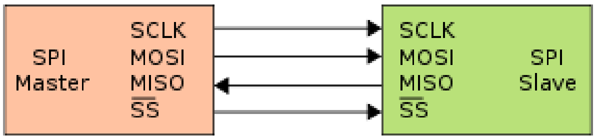


Fig. 4.20. SPI schematic

More details about SPI communication with ADIS16488 in Annexes 9.2.

4.5. Operation principles

Once the system is presented it is necessary to understand how it operates.

To sum up, there is a CPU (Overo), controlling digital ports (PWM and GPIO). It is able to reproduce the IR control signal and detect the flash trigger pulse. Moreover, it records data from IMU and timing events to use it later. The camera stores photographs on an internal SD memory. In Fig. 4.21, the basic steps that the system has to follow for a constant acquisition are shown.

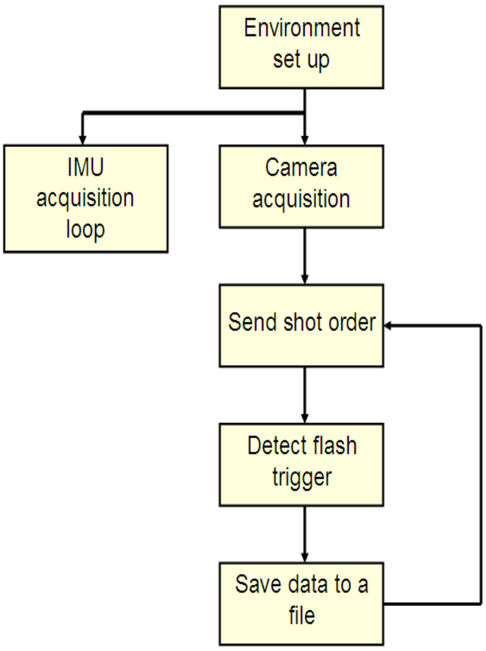


Fig. 4.21. Acquisition blocks

Environment set up includes all the processes required to start working with Overo. From USB communication with the development computer, initializing the platform and offering a terminal control interface, to driver load (PWM) and code execution.

IMU is controlled by Overo. It communicates by SPI to Overo. A file with raw inertial data from IMU is saved.

The shot order is transmitted through the PWM output and the IR circuit. Next, the flash trigger is detected by GPIO event or flag.

Then, the camera acquisition process is repeated. The processes involved on the acquisition process are synthesized on a basic flow chart below (Fig. 4.22).

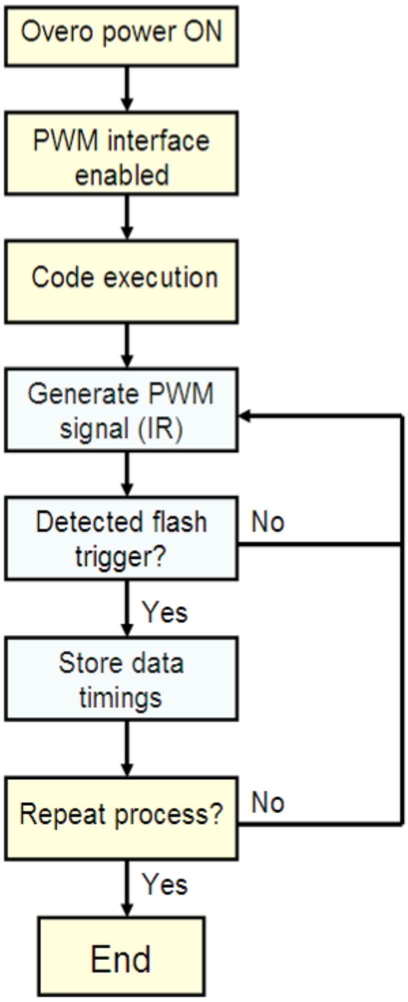


Fig. 4.22. Image acquisition flow chart

After system performance observation is decided to send the IR orders duplicated. It improves system reliability. The trigger flash event is defined on signal rising.

A prototype is build using a methacrylate structure (able to fix Chesnut43 and Pinto TH boards). Main elements and connections are identified in Fig. 4.23 and Fig. 4.24.

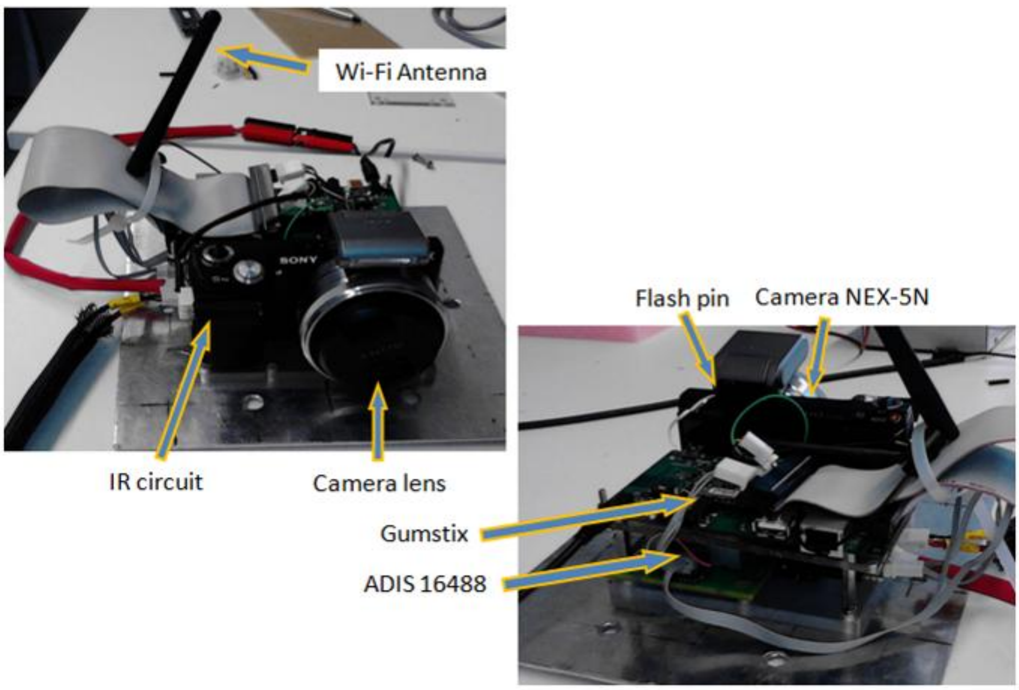


Fig. 4.23. Structure front and back views

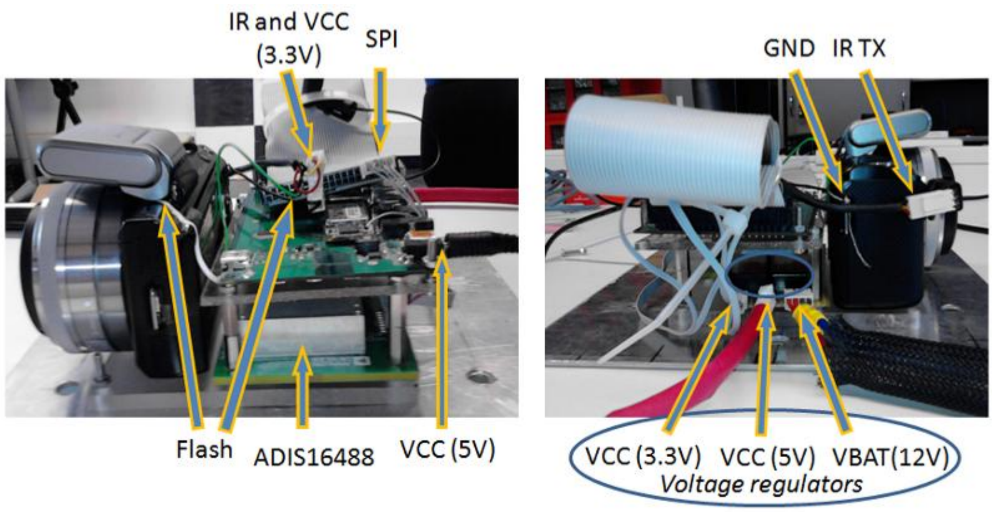


Fig. 4.24. Structure lateral views

4.6. Budget

In Table 4.5 are shown the costs related to each system element. This is useful to compare it with more expensive solutions such as mechanical gimbals.

The overall cost may be reduced by creating an own development kit (for Overo and IMU). Also, batteries and logic level converters costs can be reduced.

Furthermore, it is important to comment that several autonomous vehicles such as an UAV have its own inertial and navigation system. Therefore, the system can work with the inertial data from these systems. Then, the overall cost is reduced significatively.

Table 4.5. Budget

Component	**Cost (€)**
Gumstix: Overo	200
Chesnut43+Pinto TH	60
Sony NEX-5N + 2 lenses	700
Batteries + Logic level conv.	200
IMU ADIS + dev. kit	1500
Total	**2620**

5. Algorithms

Once data and images are captured and stored on different devices (as SD memory from camera or into a *.txt file on Overo) they must be processed.

There are many different strategies to reach image stabilization using inertial data. An IMU gives information from accelerometers and gyroscopes. In this particular case, only a single gyroscope from IMU is considered plus time stamp.

Due this, it is decided to correct rotation on perpendicular axis to camera lens (roll, see Fig. 4.3). But, once this step is successfully passed, a more complete implementation may be considered (as tilt or pitch correction).

The inertial data from a single gyroscope is processed and a file with the rotation degrees is obtained (roll axis). For that reason, a code in MATLAB is implemented. This file is used later to rotate each photo captured.

To rotate images, they are processed through and open source library called *Image Magick++*. It is available free on internet. Using this library (C++), a rotation, crop & chop functions are implemented (plus read & writing image indeed). Therefore, two main files of data are recorded, one which inertial data and other with all the flash events detected. The program must relate both files to find the rotational degree to apply at each image as represented on Fig. 5.1.

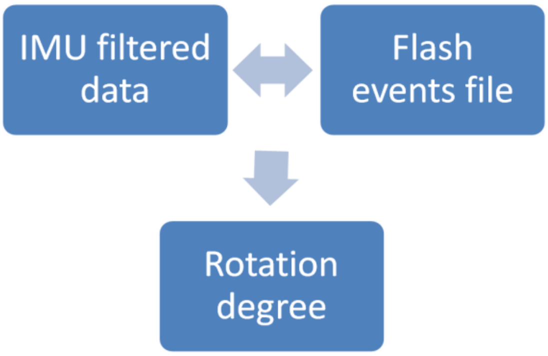


Fig. 5.1. Flash and IMU correlation

Finally, corrected images are sequenced on a video (in this case, Windows Movie Maker 2.6). To achieve a more impressive and comfortable result, a split-screen video (two screens on a single one) is presented. It is edited with a more professional video software as Sony Vegas Pro 11 o AVS.

This is because they are able to put two videos on a single screen (split screen) while Windows Movie Maker can't do it. As a result of this, anyone can observe differences on rotations for each video or solution. It results on a comparison video.

5.1. IMU data processing

From IMU a complete data flow is stored on SD (it is Overo hard disk drive). The inertial data sampling frequency (f_s) is 400 Hz (resulting on a lot of IMU samples for a single photo). Inertial data is processed using IMU equations (section 4.2). MATLAB is responsible of IMU data filtering/reduction (typ. 1:10) and, if necessary, improve measurements:

- To reduce length and/or filter IMU data.
- To improve inertial measurements.

Traditionally, INS mechanization equations are used to calculate system motion by inertial data from the accelerometers and the gyroscopes ([19], [44] and [45]). They are commonly used on navigation or arms industry ([46], [47] and [48]). The project approach considers only a single gyroscope. Therefore, photographs are only corrected on roll axis. However, this approach reduces system accuracy.

For a single axis correction, an example of a mathematic function, reducing data length by 10 and calculating roll angle (rotation), is:

$$rotation(k) = rotation(k-1) + \frac{N}{f_s}\sum_{n=1}^{N} sample(n)$$

The beginning and ending of all tests are well known (same spot and orientation, see section 6.1). Moreover, the system is quiet on a more or less flat terrain each few times. It is known that some errors are going to affect system performance (section 4.2). Due this, static bias is measured at the beginning.

Thus, results in a non-desired rotation on photos. It may be because of biasing accumulative error effect. This means, IMU accumulates errors on measures, being added to the “ideal” value and distorting rotations measurement. With the pass of time, the error increases being the effect more and more visible.

Data filtering (downsampling) reduces high frequency components not desired for this solution.

To improve the inertial measurement, two options are considered. The first one, is the calculation of a tendency equation (a polynomial). Subtracting it, errors can be reduced. As more complex is the calculated equation (higher degree polynomial), more precise is the correction. But, then is more complex to obtain and process it. Different polynomials are studied of different degree (form 10^{th} to 2^{nd}).

Moreover, stops detection reduces the possible error to. It restarts the calculated rotation to 0 if the sample value is in noise levels (see Annexes 9.2). Must be mentioned that, for this chapter, all the graphs shown are related to the dynamic test 1 (see section 6.3.2).

5.1.1. IMU data filtering

IMU sampling rate is 400 Hz. But for project purpose, it is not mandatory to work with full samples rate. Downsampling is used as a noise filtering function. For that reason, different windows size of 5, 10 o 20 samples are implemented. A larger window results in fewer samples and less accuracy but it can be sufficient. Data is multiplied by a scale factor (s_f) depending on the number of end samples (more samples, less weight each sample has on the global). Depending on N (window size):

$$s_f = N/400$$

Therefore, as an example, for 10 samples, s_f value is 0.025, and for 20 samples it is 0.0125. In Table 5.1, results from each window size are compared (marks are referenced to Fig. 5.2).

Table 5.1. Window data filtering comparison

	N (samples)		
Mark	**5**	**10**	**20**
A	-4.83	-4.831	-4.832
B	3.821	3.835	3.829
C	45.48	45.5	45.49

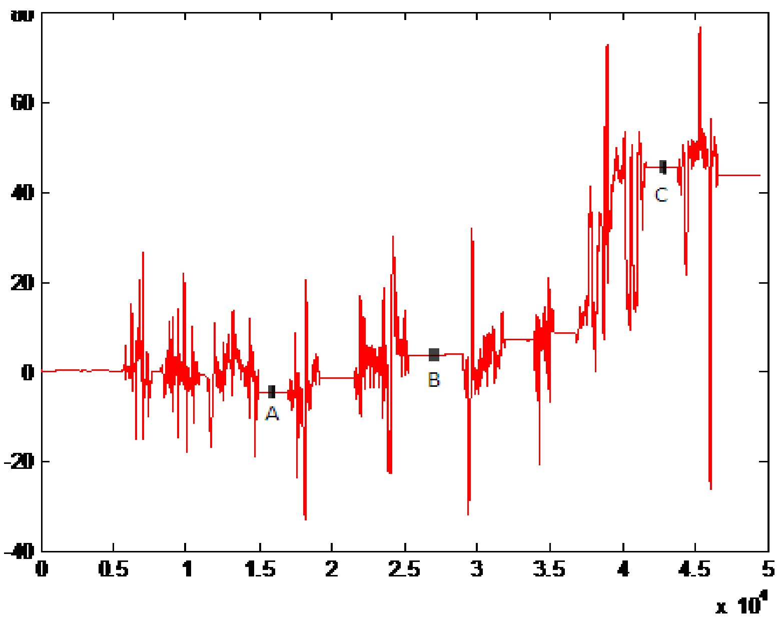


Fig. 5.2. Original data shape (N = 10)

It can be appreciated a small but not-significant differences between them. As they have a similar length respect to the total number of samples per seconds (approx. from 2.5% to 1% of the total) it has not found significant differences. For that reason, any of them are considered as a good option. But it is decided to work with a ten samples (N) filter.

5.1.2. Strategies to improve attitude solution

It is well known that IMU is going to add an error on measurements along time (time drifting). This effect is easily appreciated after images processing review. Therefore, some data corrections are considered and two of them have been evaluated:

- Error fitting by polynomial subtraction.
- Stops detection.

The first one considers an accumulative tendency onto the error:

$$\omega_z(measured) = \omega_z(ideal) + e(t)$$

Therefore, a subtraction is considered to reduce this error and obtain an approximation of the ideal value. Matlab calculates, in a fast way, a polynomial of a function (*polyfit()*):

As a example, in Fig. 5.3, a 5th and a 3th degree polynomials are shown.

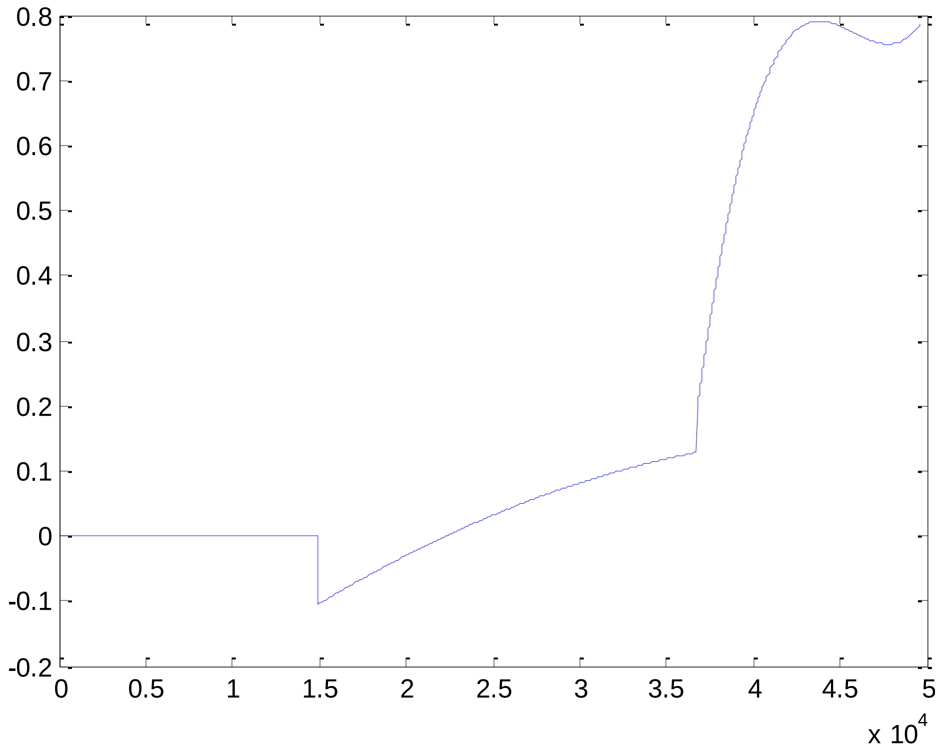


Fig. 5.3. Polynomial representation

Subtracting this function (Fig. 5.3) from obtained data (Fig. 5.2) it is obtained a more realistic motion function (Fig. 5.4).

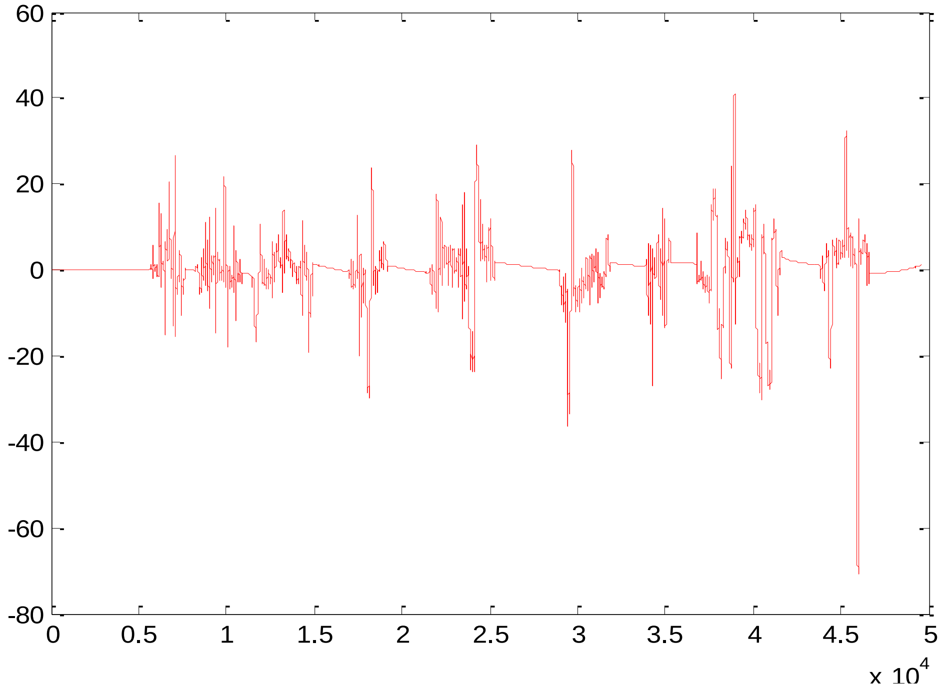


Fig. 5.4. Polynomial correction

The second one detects stops by knowing IMU performance on a stop situation. From IMU datasheet, stops can be identified if angular rate is, in absolute value, less than 6 deg/hour (3e-5 rad/s) for N samples (see 9.2).

In Fig. 5.6 is shown the raw inertial data from a single gyroscope (z axis).

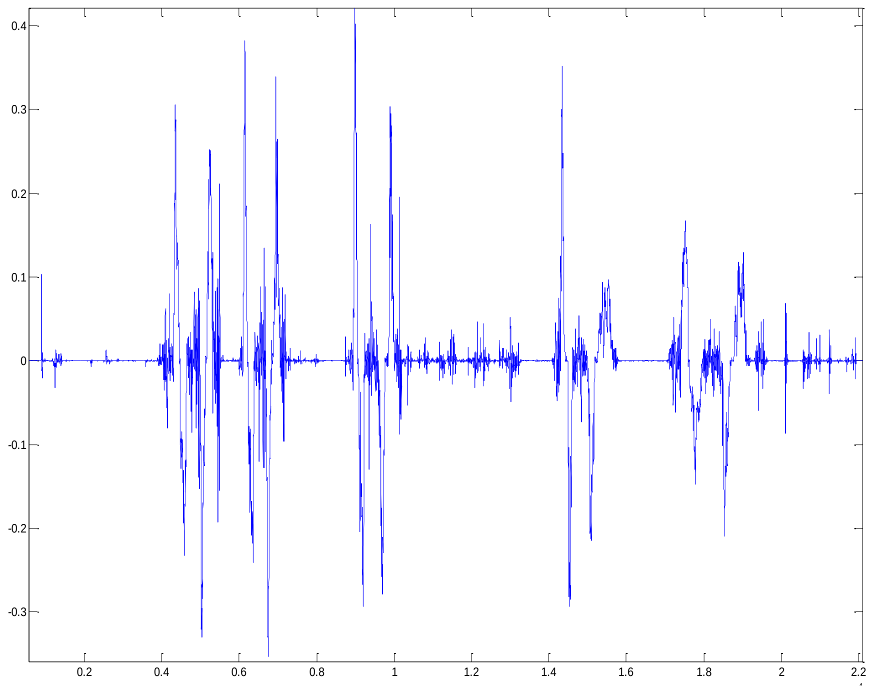


Fig. 5.5. Single gyro raw inertial data

While in Fig. 5.6 it is shown the solution obtained after stops detections solution is applied.

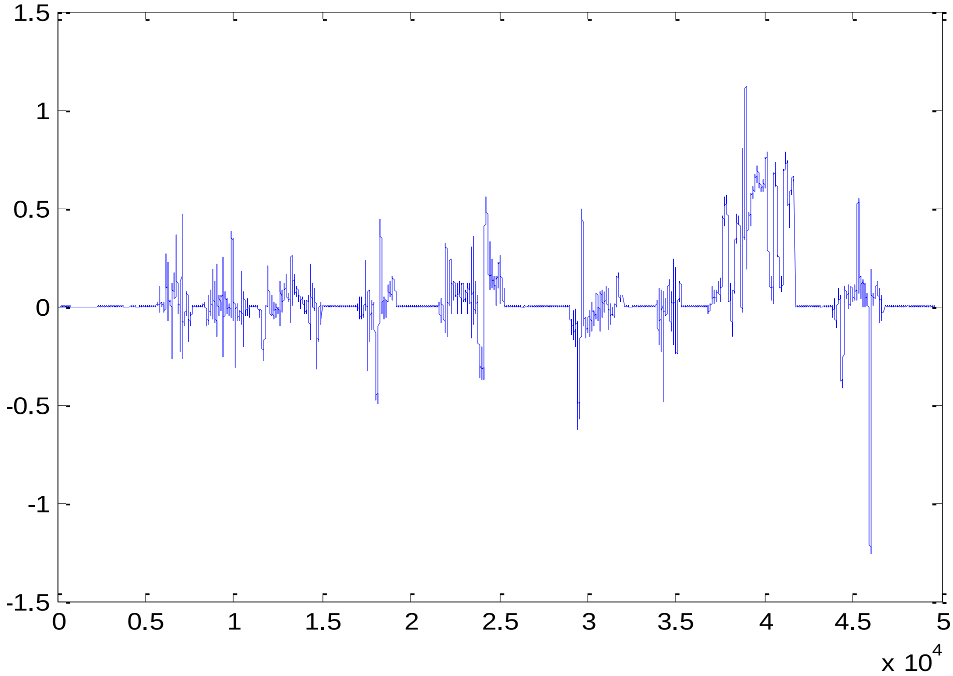


Fig. 5.6. Stops detection

5.2. Image edition

It is a constraint of the project to edit photos in order to compensate camera rotations. Photographs are rotated using angular rates calculated from processing the raw inertial data file.

To process the photographs, an open source image library is used. It is called *ImageMagick*[7]. Moreover, it can be found more extra functions for the library adapted to Linux and an API version is offered for windows users. Also, it can work by command line in a console terminal.

Magick++ is a C++ API to the *ImageMagick* library. It has been used with Microsoft Visual C++ 2010 to have access to library functions. This API is able to load, resize, apply filters, rotate, etc… images on a big variety of extensions, such as *.jpg*, *.png* or *.bmp*. For the project purposes it is necessary to call only some of the available functions.

Each rotation is calculated respect to the first photo. This is because at the beginning, system is stopped to calibrate it. The process is sequenced in Fig. 5.7:

[7] http://www.imagemagick.org/

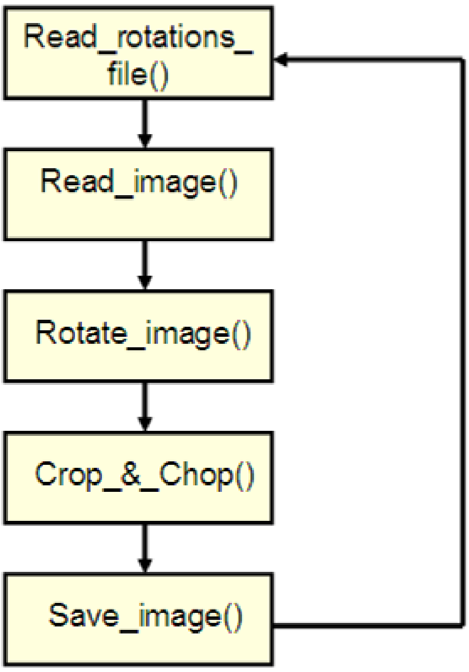


Fig. 5.7. C++ code schematic

After rotation correction is applied, each photo has a different pixel size. For that reason, a crop and chop is applied. With this, all images are resized to a normalized size (2000x1000).

It results on a zoom effect but standardizes photographs size. It is important to apply rotations on the opposite sense to the measurement.

In Fig. 5.8 can be observed, at the left side, the original image. At center, the rotation effect. A crop and chop effect are applied on the right side (photographs are from lab test, section 6.3.1).

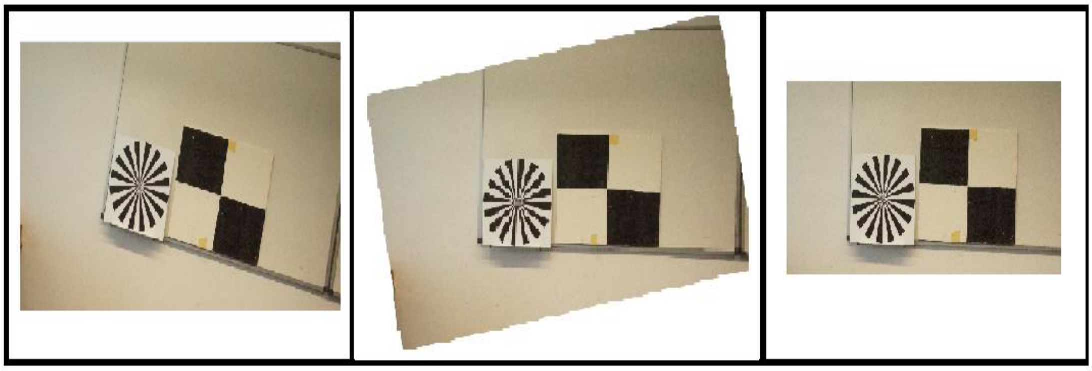


Fig. 5.8 Image rotation and size reduction effects

It must be mentioned, that both functions are applied to all images.

5.3. Video edition

A sequence of photographs are obtained from the camera and rotated. Next, a sequence is done taking all the photographs. Due the large amount of photographs taken, it is defined a small period for each one (0.25 sec) in order to obtain a video.

Furthermore, a split screen video is used to evaluate and compare results (as an example, comparing the initial and an improved method). Videos are edited with AVS.

The stabilization global performance can be appreciated watching the video. A sample screen is on Fig. 5.9, being the upper screen the original one while the lower is the corrected.

Fig. 5.9. Split screen video sample

Next, photo-by-photo comparison can measure and observe better the changes applied to each image (see Table 6.2 and following)

6. Verification and validation

6.1. Tests definition

Once all the system was correctly configured and working, several tests have been proposed to evaluate the system performance. They were divided into two groups.

The first one, was the camera test performance. There were tested the camera acquisition stability (6.2.1) and the camera acquisition procedure (6.2.2). All these tests were done at the laboratory. The second one, was the system test performance. One test was performed at the laboratory (6.3) and two outside the laboratory (6.3.2 and 6.3.3).

Therefore, camera acquisition stability was evaluated. For this test, the camera was set to take photographs at a constant rate. It was tested the frame per second ratio and the time response from IR order begins to image acquisition starts.

Next, flash trigger has been tested to know the delay between its beginning and the moment when a photograph is acquired by the camera. This has been done using a 7-segment LCD (showing number from 0 to 9 at 0.3 ms period). It is controlled by an Arduino (MCU). It begins the numerical sequence once an internal interruption detects the flash trigger event. Therefore, the numbers acquired on different sensor spot (upper left, center, upper right …) determine the camera performance.

Then, the stabilization performance was verified and validated. All the elements were mounted on a methacrylate structure. It was fixed to a small aluminum platform (Fig. 6.1).

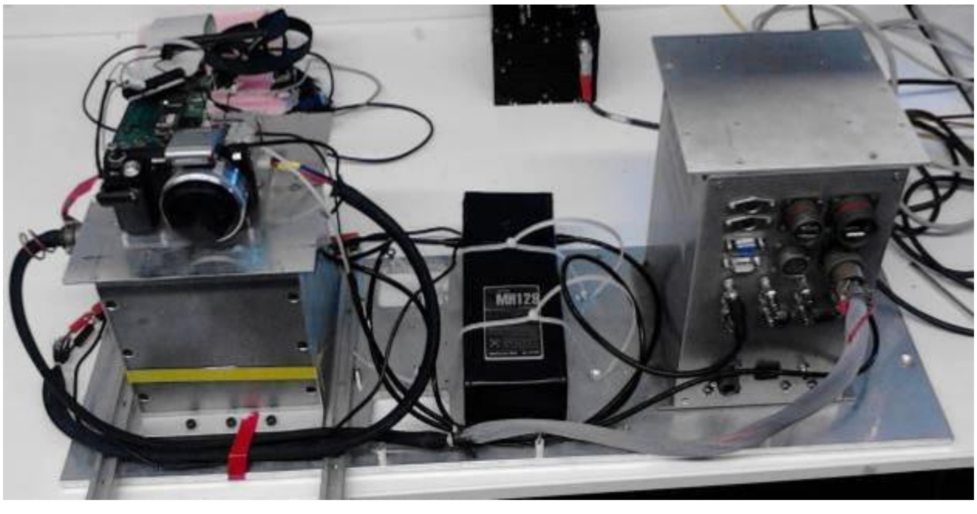


Fig. 6.1. Test platform

The entire platform was oriented perpendicular to a white blackboard with two calibration patterns to observe better photographs rotations.

The aluminum platform was rotated, as best as possible, on a single axis (perpendicular to the camera lens).

After that, a more complex and complete test was performed using the same platform. This time, the platform was moved across the IG building and surroundings. In this test, the structure was moved on the 3 axis by hand, 15 minutes walking, with some stops. It has been intended to put it on hard situations as stairs crossing or heavy and unusual rotations.

Finally, due the results observed on previous test (in section 6.3.2) it is decided to perform the last test. The platform went on a small trolley fixed strap down. It was driven on a half pipe (Fig. 6.2) that causes mainly rotation on a single gyroscope axis (perpendicular to camera lens).

Fig. 6.2. Trolley at Half pipe

All the tests were done using LN-200 IMU. This is because ADIS16488 IMU has not been yet integrated (SPI communication is not developed). It is not part of this project to develop a SPI communication between the IMU and the CPU. But, the entire project is defined to use the ADIS16488 IMU as inertial data sensor. Due this, ADIS16488 was simulated from a tactical grade IMU (LN-200, see Annexes 9.6).

6.1.1. IMU simulation (from LN-200 to ADIS16488)

As commented before, system was initially projected to work with a low cost IMU (ADIS16488). It is simulated from a tactical grade IMU (LN-200). It is connected to its own processor (a system developed previously by IG). This system saves data files with flash synchronization events and IMU inertial data. In order to have the same angular specifications it is required to add to the rotations (ω) file:

- White noise (a_t).
- A bias (b).

$$\omega_z(ADIS) = \omega_z(LN200) + b + a_t$$
$$b = 0.002$$
$$a_t \approx N(0, 1.7e^{-3})$$

Simulation offers the possibility to compare both IMUs in a simple way without hardware changes or test repeating (or if one is not ready as occurred). For a more precise and accurate comparison ADIS may be tested side by side with LN-200. Therefore, corrected videos, each with its own IMU data, will be compared.

After emulation, a new rotation data file is obtained and used as rotation data file (Fig. 6.3):

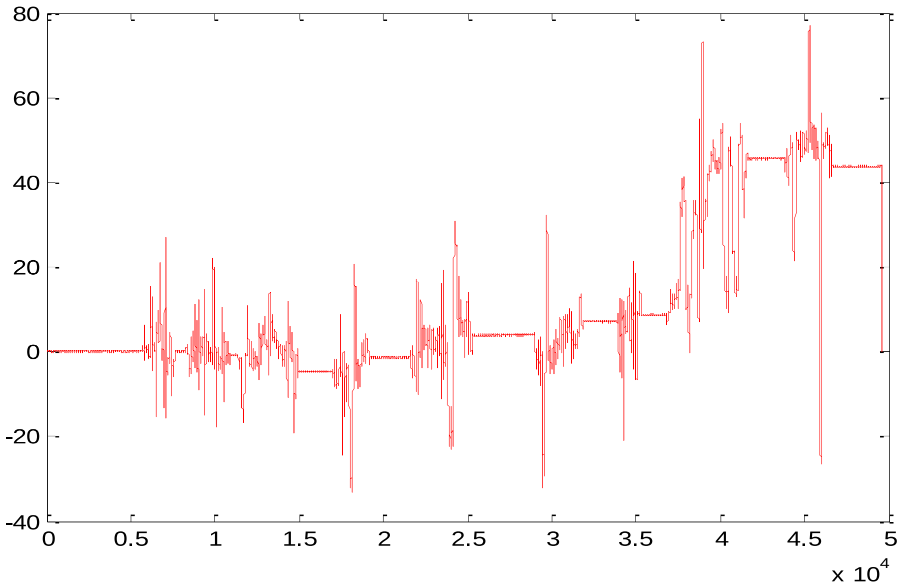


Fig. 6.3. ADIS16488 z-gyro rotation data simulation

6.2. Camera performance tests result

6.2.1. Camera time response and constant flow analysis

For some projects is important to achieve a fast response to IR or shot order and/or a constant delay (flow) between photographs. These are evaluated in order to see the system performance.

There are tested two camera operation modes (manual and auto intelligent). This data can be useful to determine the best operating mode (the faster or the more stable, as examples).

By one hand, it has been tested manual mode in Fig. 6.4 (IR timeout = 0.7 ms). This figure shows the time increment from two consecutive flash signal events. Manual mode means all camera parameters are configured by hand previously (such as focus, focal aperture, exposure time…).

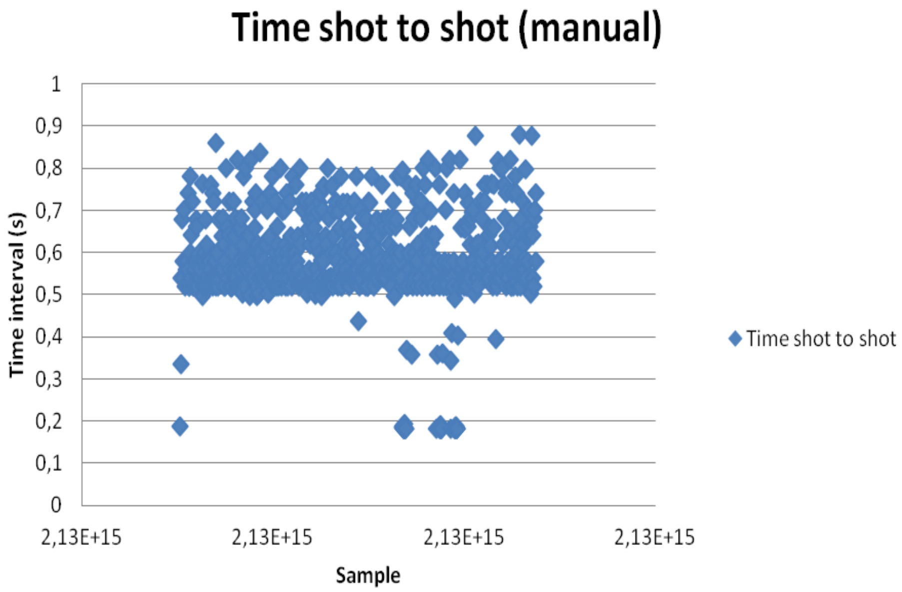


Fig. 6.4. Timing manual mode

Most of the samples (photographs) are below 0.6 seconds, but this time is not constant. Its mean is 0.56 s (1.8 fps) and a standard deviation of 0.14 s. This time includes also the time needed for the camera to store the photograph.

By other hand, it has been tested the auto intelligent mode (Fig. 6.5). Auto intelligent mode means camera controls all the parameters (such as focus, focal aperture, exposure time…). This figure shows the time increment from two consecutive flash signal events.

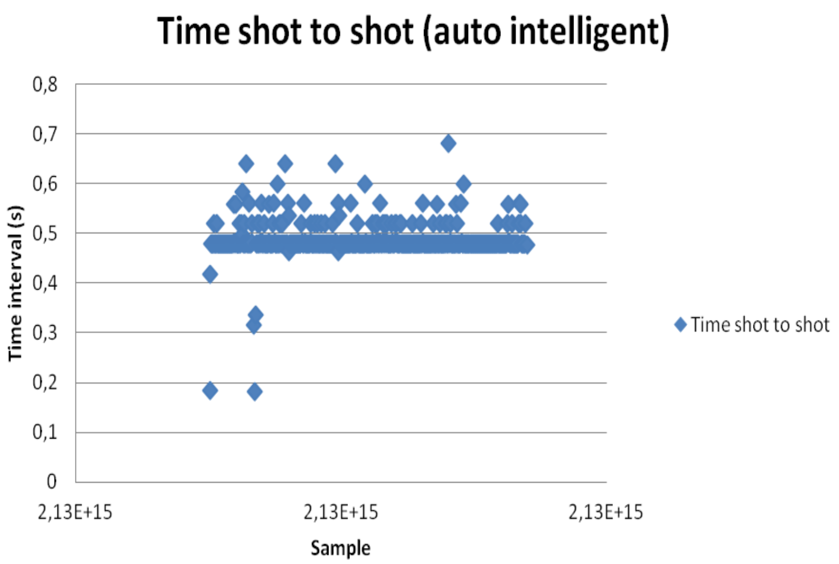


Fig. 6.5. Timing auto intelligent mode

Most of the samples are under 0,5 seconds, its mean is 0,48 s (2 fps) and a standard deviation of 0,03 s (better than before). Delay is not constant but it seems “quantizable” (timing levels). It might be as a result of some kind of auto mode clock quantization. Moreover, it shots faster than manual mode. It is important to remark that the exposure time is automatically fixed in auto mode. This might be the reason why the time from shot to shot is shorter than in manual mode.

For both tests, less than 2% of the time no IR order has been detected, resulting on a timeout. Timeout is programmed by software and then, the IR order is repeated. This is why some photographs required more time to be taken. Furthermore, it can be appreciated that camera doesn't shot at a constant ratio. Sometimes the camera works faster. This can be because of some kind of IR orders buffer. This buffer allows the camera to shot two consecutive photographs quickly.

Moreover, the time required to process the IR order and to start image acquisition is around few hundreds of milliseconds. This timing is shown in Fig. 6.6. This figure shows the time increment from an IR order is emitted and the flash signal event is detected. Its shape is similar to previous graphs (Fig. 6.4 and Fig. 6.5).

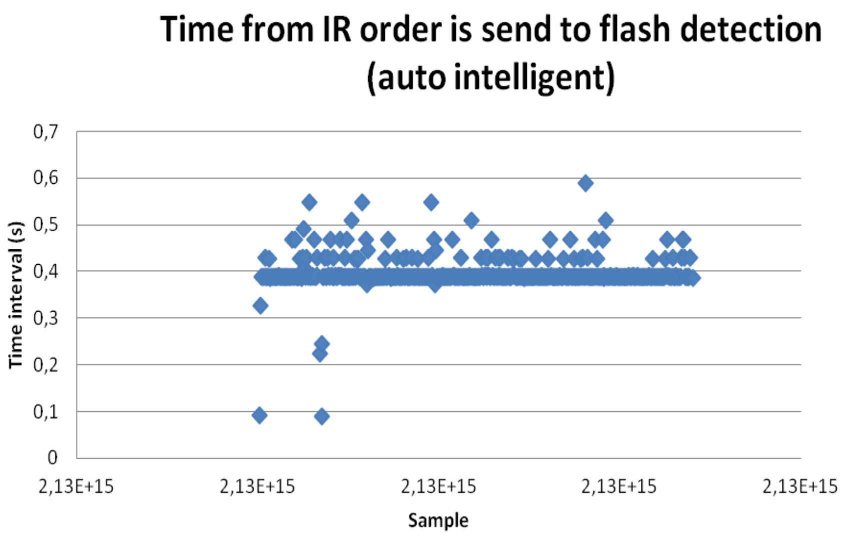


Fig. 6.6. Camera IR time response

This limits the camera performance if a fast IR response is required. But IR allows to work wireless with the camera. It reduces the shutter release control complexity and avoids possible camera malfunctioning due more complex solutions such as camera opening.

6.2.2. Flash trigger as image acquisition reference

Measure the delay between the flash trigger pulse and image acquisition is useful to evaluate and validate latter results. This is used to determine better the camera performance. Flash trigger limits camera to a maximum speed of 1/160. It may not be fast enough to take photos on a speedy device as a car or an aircraft. That is the reason why it is measured. Moreover, how the camera works for faster speeds is important to know.

Camera is set to 1/4000 speed, and a non-expected solution is implemented on it (to achieve this speed with flash signal). The camera divided the total length in some parts (as observed on Fig. 6.7), acquiring each part during 1/4000 seconds, but in different time instant.

This results on a tricky. Each part is correctly acquired at the selected speed, but the global timing for image acquisition is closer to 1/160 (the camera limit with flash). Therefore, a photograph is created by the union of small photographs. By this way, the number represents the delay from flash trigger to image acquisition (see Fig. 6.7, the number increases by one each 0.3 ms after flash trigger signal starts).

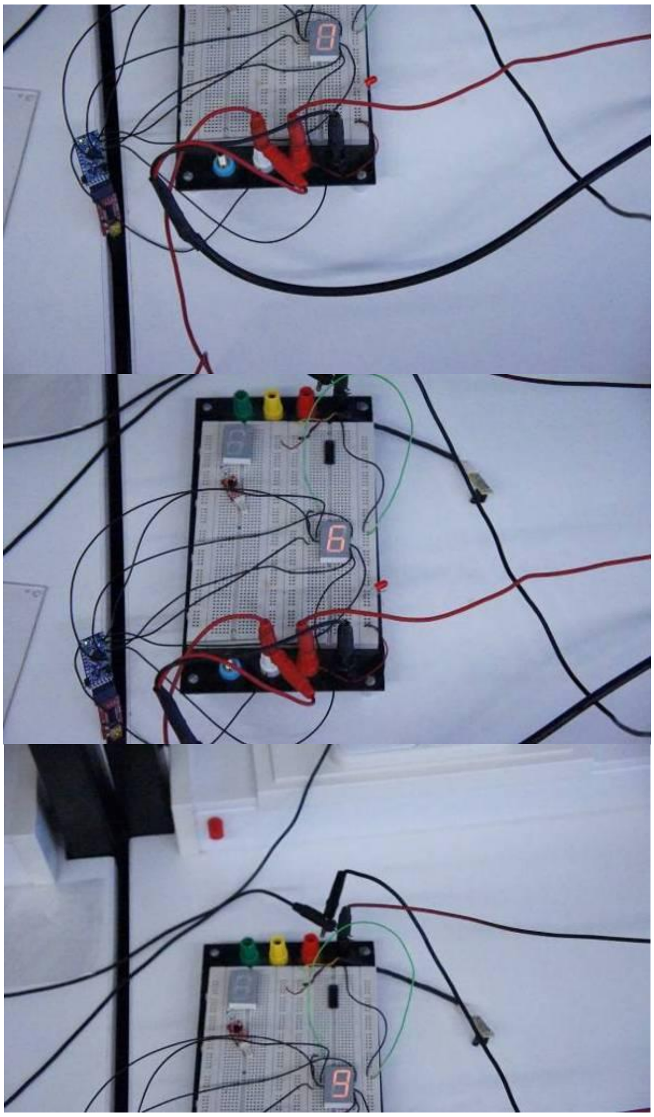


Fig. 6.7. Image acquisition test (numbers 1, 6 and 9)

The results obtained shown as camera begins to acquire images before 1 millisecond (numbers 0 to 2). It goes from up to down, acquiring last frames 2 ms later, approximately (number 9). For speeds 1/160 and lower, image acquisition started 1 or 2 ms after flash trigger pulse begins.

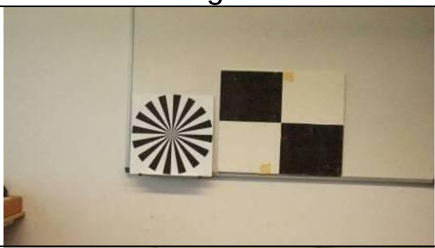
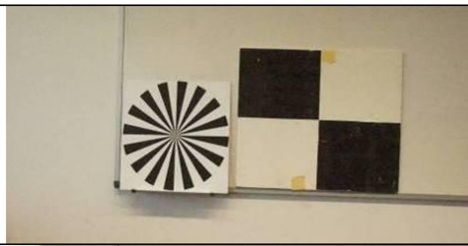
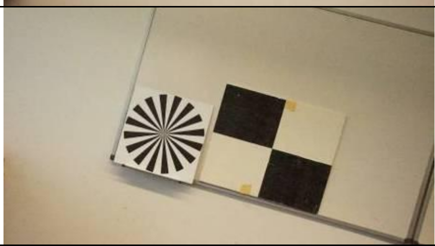
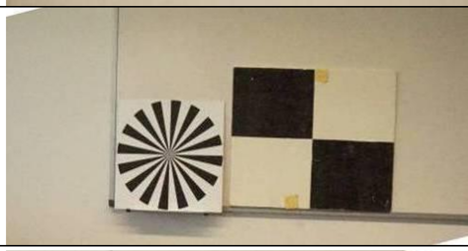
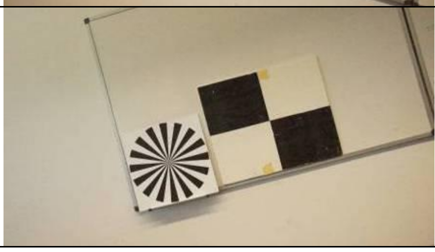
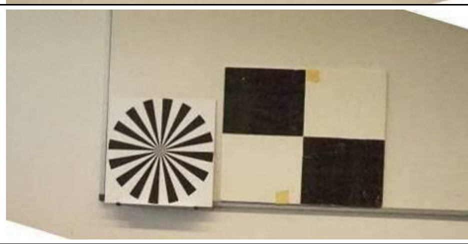
6.3. System performance tests result

6.3.1. Lab test

At the beginning, a static period is measured to reduce the bias effect (1 minute). It is measured to improve rotation angles calculation. For this test rotations are calculated using only single-axis measurements (z-gyroscope, section 4.2). For this test has been taken 119 photos at 1 fps.

Some stabilized photographs are shown in Table 6.1. It is used a 10 samples window. For this test only a single solution is applied, the initial solution (section 5.1). This is good enough for a short-time single-gyro rotational correction. Its error level is not eye-observable at big part of the photos. Furthermore, a zoom effect is produced due new images are smaller (crop and chop functions are applied to each photograph). Each photo is identified with the camera tag name, the rotational angle applied to the corrected image and its sequence number (#).

Table 6.1. Lab results analysis

	Original	Corrected
DSC-2410 α < 0.1º (#82)		
DSC-2432 α = -14º (#104)		
DSC-2440 α = 16.8º (#112)		

Therefore, system is able to correct single axis rotations as observed, obtaining a stabilized sequence. Small errors are appreciable (around 1 degree). All these results, as commented before, are obtained with ADIS16488 inertial data simulation.

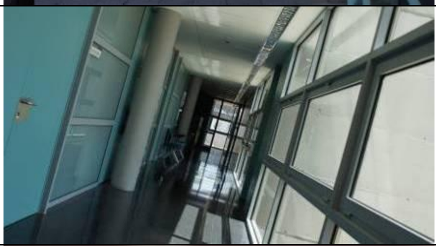
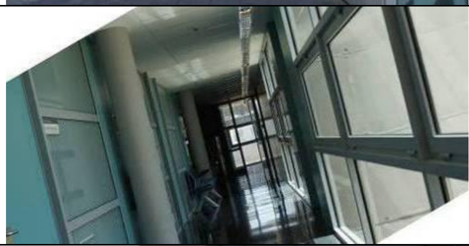
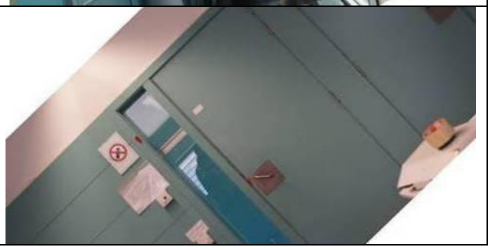
6.3.2. Dynamic test 1

For this test is performed a long time walking across the IG building and surroundings. It started and ended at the same spot, inside the IG laboratory.

The test platform is moved by hand and some stops are performed during the test realization. The platform is moved in heavy rotational angles deliberately. There are captured more than 700 photos at 1 fps. Moreover, the three proposed solutions are evaluated (initial, polynomial and stops detection, section 5.1.2).

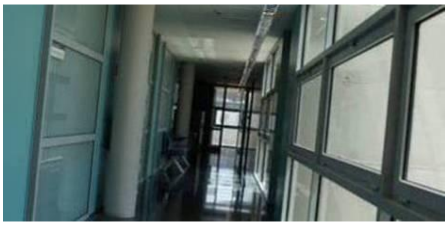
A few frames using the initial solution are shown in Table 6.2. This solution presents a bias error effect across the time. This effect is so notorious at the end part of the test. Thus, last photographs have an offset rotation angle (such as #601 and #736, below).

Table 6.2. Initial correction

	Original	Corrected
DSC-2910 α = 4.8º (#178)		
DSC-3333 α = -29.3º (#601)		
DSC-3468 α = -43.6º (#736)		

For the polynomial solution the bias error is reduced. The polynomial solution implements a 3^{rd} and a 5^{th} degree polynomials (Fig. 5.3). A few samples are shown in Table 6.3.

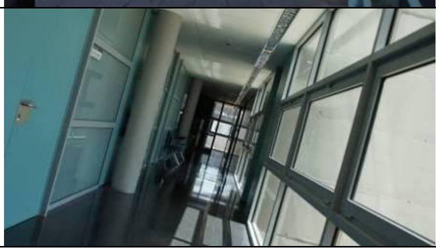
Table 6.3. Polynomial correction

	Original	Corrected
DSC-2910 α = 1º (#178)		
DSC-3333 α = -9.6º (#601)		
DSC-3468 α = 0.8º (#736)		

A small deviation from measured to ideal is obtained in few photographs (such as #601). This is because the calculated polynomial is only an approximation, sometimes closer to the ideal solution but sometimes not. Also, on a stop situation (such as #736), a small deviation (around 1 degree) from real value is appreciated.

While, in Table 6.4 are shown a few photographs for the stops detection solution.

Table 6.4. Stops detection

	Original	Corrected
DSC-2910 α < -0.1º (#178)		
DSC-3333 α = -20.6º (#601)		

DSC-3468 α = 1.9º (#736)		

The stops detection solution works well enough at each stop (#736). Instead, it doesn't reduce errors present between two stops. The error it is not corrected until a new stop is detected. Must be mentioned that is observed a "jump effect" at each stop. This means, correction is not gradual along the tests. It causes an appreciable rotation angle difference between the photograph before and after the stop detection.

Both solutions improved considerably system performance. Specially after watching them on a video. They are evaluated below (Table 6.5):

Table 6.5. Data correction performance

	Polynomial correction	**Stops detection**
Strengths	Global approximation is good enough. Corrects errors during a long time mission.	Delete any error after few stop samples (like a reset function).
Weaknesses	Not appropriate for very fast changes (not common). Small errors on stop situations.	"Jump" effect before stop detection. Don't correct the bias error between two stops. Not always a stop can be performed on tests (such as on a UAV).
Conclusions	Good enough for all situations.	Better than polynomial solution if several stops can be performed.

It can be observed a tremulous effect if compared with a LN-200 IMU graph (from Fig. 6.3 to Fig. 5.2, respectively), not so heavy (the shape of the function is not affected) but appreciable on a video by small "vibrations" on screen. This effect is appreciable at stops, while when system is moving it is not appreciated by eye seeing.

6.3.3. Dynamic test 2

This test is proposed to observe better rotational corrections. It is performed on a half pipe structure. This reduces possible not-desired lateral and vertical movements. The tests conditions are similar to "Dynamic test 1" (such as windows size, section 6.3.2). It is evaluated with initial, polynomial and stops detection solutions. Working on automatic mode, the camera is able to offer a constant speed ratio around 2 fps. The test is 5-10 minutes long. In Fig. 6.8, single-gyro (z axis) rotational calculations are presented:

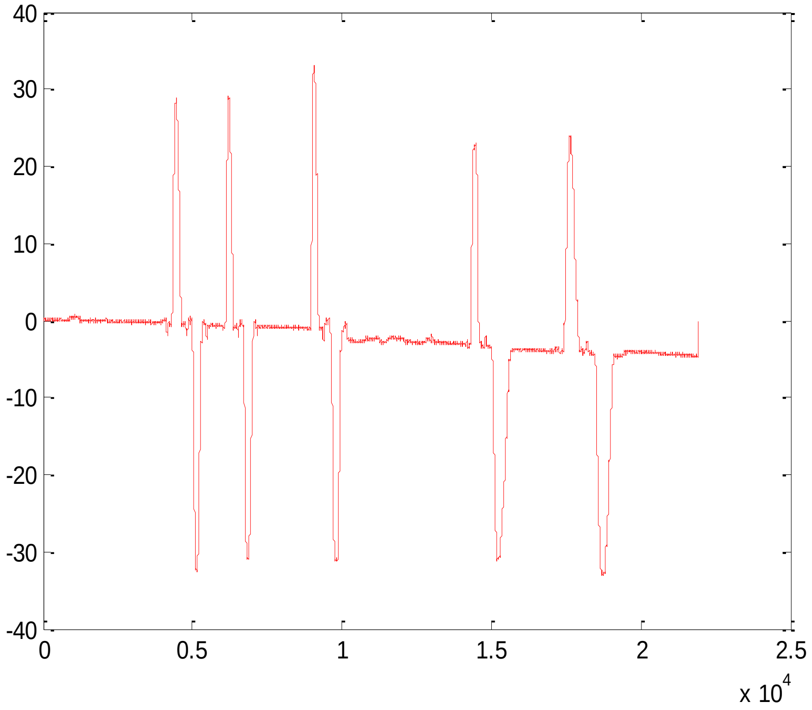


Fig. 6.8. Dynamic test 2 graph

To begin, photos are processed by the initial solution (Table 6.6).

Table 6.6. Initial correction

	Original	Corrected
DSC-4870 α = -20.3º (#159)		

DSC-5015 α = 31.2º (#304)		
DSC-5250 α = 4.4º (#539)		

As before, it presents a bias error across the time.

This time, the polynomial solution (Table 6.7) implements a 2^{nd} degree polynomial.

Table 6.7. Polynomial solution

	Original	Corrected
DSC-4870 α = -21º (#159)		
DSC-5015 α = 28.7º (#304)		
DSC-5250 α = -0.7º (#539)		

The stop detection solution is shown in Table 6.8.

Table 6.8. Stops detection

	Original	Corrected
DSC-4870 α = -20.7º (#159)		
DSC-5015 α = 30º (#304)		
DSC-5250 α = 0.2º (#539)		

Results are similar to dynamic test 1. A small error is appreciable on last photographs for the polynomial solution. The stops detection solution offered the best performance in this test.

7. Conclusions and outlook

After project implementation, it is validated a low cost camera stabilization system by implementing and analytical gimbal. At least, using a single-gyro inertial data, it worked accurately. Some rotational deviations appeared (along testing time). But two supplementary solutions are presented to improve the system performance.

For better performance, a 6 axis method (3 gyros and 3 accelerometers) must be implemented. This method has to implement the mechanization equations commented previously (see section 4.2). They are studied for this project but due its level of complexity and time requirement are not implemented. This will result on more accurate solutions. For a single axis correction, the project simplified the equations used working with a single gyro inertial data (discarding two gyros and the accelerometers). It results in a small deviation on rotational calculations.

The project covered a lot of aspects from its low step, being able to control or modify almost everything. The inertial data from the IMU unit can be processed with different methods and filtered in different ways. The decision to work with open source hardware, as Overo Gumstix, has allowed full control over the system. It has been done an image and a driver compilation to multiplex PWM output and enable the SPI communication. It has been generated the correct IR signal to control a specific camera. Moreover, an interruption has been programmed to detect the flash trigger signal on a GPIO input port. The timing and events are logged for synchronism.

Instead, it results in a long time development platform, such as kernel compilation for SPI. As SPI interface was not validated by IG during the project implementation, the selected IMU was simulated using the inertial data from a tactical grade IMU (LN-200). From simulation results, can be determined that the IMU offers enough quality level for image stabilization.

The camera showed good results while few weaknesses have been found. By one hand, an IR remote control has been realized. It controls wirelessly the camera shutter release (and video). The IR camera interface not actuates instantly on the camera shutter release. By other hand, flash trigger, has been observed as a good reference for image acquisition timing, but it limits camera performance (particularly exposition time). There are few cameras able to reach higher speeds with flash enabled.

Camera is able to work at a speed around to 2 fps by more than an hour, continuously. It presented an image quality so good (big sensor and good resolution) for actual commercial grade cameras. As it works with an SD memory, it saves photos fast. For real-time processing it is desirable to work with an external photo storage device, able to have this information available at a computer. Its weight, size and price make it ideal for low cost implementations.

7.1. Outlook

Some improvements and future ideas can be added after the project development.

The camera IR shutter release control is observed variable and slow. There are other possibilities for other camera models faster, such as by USB. Also, the camera can be opened and an external switch can be soldered directly to the shutter release control ([49] and [50]). This is electronically complex and risky because IG has only a single camera unit.

It is important to continue developing the code in order to use a complete INS solution. For that, it is required to use the mechanization equations. It will improve the system performance. A GPS can be included to improve system reliability.

Furthermore, it is corrected correctional rotations on a single axis. But it can be developed a system correction one more axis. Pitch or yaw correction can be a constraint for future image stabilization projects and researches.

The stabilization system is designed considering a small but high performance IMU unit (ADIS16488). The inertial data from this unit is simulated from a tactical grade unit (LN-200). In a future, the ADIS16488 IMU can be used to prove the good results obtained from the simulation.

To reduce the system weight and size, it is interesting to continue the system development using the Pinto TH board. A Wi-Fi communication can be used for files transferring (due its lack of console terminal or Ethernet pin, Fig. 7.1).

Fig. 7.1. Pinto TH and Wi-Fi antenna

Finally, this system is a solution whenever the project budget is not enough for a gimbal solution (which costs some hundred times more than the solution offered by this project).

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9. Annexes

9.1. Sony NEX-5N

Specifications:

Drive System

- Burst Buffer : JPEG (Fine: 10 shots, Standard: 10 shots), RAW (6 shots), RAW+JPEG (4 shots)
- Drive Mode : Single-shot, Continuous, Speed Priority, Self-timer, Continuous Self-timer, Bracketing
- Shutter Speeds : 1/4000 to 30 seconds, bulb
- Shutter Type : Electronically-controlled, vertical-traverse, focal-plane shutter

Focus Control

- AF Modes : Single-shot AF, Continuous AF, Direct Manual Focus, Manual Focus
- Focus Area : Multi Point AF (25 points), Center Weighted AF, Flexible Spot AF
- Focus Sensitivity : 0 EV to +20 EV (at ISO100 conversion with F2.8 lens)
- Manual Focus Assist : Magnified display for precise manual focus
- Focus Features : Predictive Focus Control, Focus Lock
- AF Illuminator : Built-in, LED type

LCD Display

- LCD Type : 3.0” TFT Xtra Fine™ LCD (921,600 pixels) w/TruBlack™ technology
- Angle Adjustment : Up: Approx. 80 degrees, Down: Approx. 45 degrees
- Brightness Control : Auto, Manual (5 steps between -2 to +2), Sunny Weather
- Coverage : 100%
- Live View : Yes, (Constant AF Live View)
- Real-time image adjustment display : Exposure Compensation, WB, Creative Style
- Histogram : Yes (On/off)
- Peaking : Yes (MF only, Level setting: High/Mid/Low/Off), (Color: White/Red/Yellow)
- Grid Display : Yes (On/off)
- Customization : Brightness: Auto, Manual, Sunny Weather; Display Color: Black, White, Blue, Pink
- Touch Panel : Yes

Recording

- Media Type : Memory Stick PRO Duo™/Pro-HG Duo™/PRO-HG HX Duo™ media SD, SDHC and SDXC memory card
- Color Space : sRGB, AdobeRGB
- Still Image Mode : JPEG (Standard, Fine), RAW, RAW+JPEG

- Still Image Size 16:9 : L (14M): 4912 X 2760 M (7.1M): 3568 X 2000 S (3.4M): 2448 X 1376
- Still Image Size 3:2 : L (16M): 4912 X 3264 M (8.4M): 3568 X 2368 S (4M): 2448 X 1624
- Panorama Still Image Size : Horizontal Wide: 12,416 x 1,856 (23M) Horizontal Std.: 8,192 x 1,856 (15M) Vertical Wide: 2,160 x 5,536 (12M) Vertical Std.: 2,160 x 3,872 (8.4M) 3D Sweep Panorama: Horizontal Wide: 7152 X 1080 (7.7M) Horizontal Std.: 4912 X 1080 (5.3M) 16:9: 1920 X 1080 (2.1M)
- Video Format : AVCHD / MP4 (MPEG-4 AVC (H.264))
- Video Mode : AVCHD: PS - 1920 x 1080/60p@28Mbps FX - 1920 x 1080/60i@24Mbps FH - 1920 x 1080/60i@17Mbps FX - 1920 x 1080/24p@24Mbps FH - 1920 x 1080/24p@17Mbps MP4: HD - 1440 x 1080/ 30p@12Mbps VGA - 640 x 480/ 30p@3Mbps
- Video Signal : NTSC color, EIA standards
- Audio Format : Dolby Digital (AC-3) / MPEG-4 AAC-LC
- Microphone/Speaker : Built-in stereo microphone; Built-in, monaural speaker
- Still Image File Format : JPEG (DCF Ver. 2.0, Exif Ver.2.3, MPF Baseline compliant), RAW (Sony ARW 2.3format), 3D MPO (MPF Extended compliant)

Weights and Measurements

- Dimensions (Approx.) : Approx. 4-3/8 × 2-3/8 × 1-9/16" (110.8 x 58.8 x 38.2mm) (W/H/D) excluding protrusions
- Weight (Approx.) : Approx. 7.4 oz (210g) (excl battery & media) Approx. 9.5 oz (269g) (w/battery & media)

Advanced Features

- Face Detection : On/On (Regist. Faces)/Off
- Smile Shutter™ technology : Smile shutter (selectable from 3 steps)
- Auto High Dynamic Range : Yes, (Auto Exposure Difference, Exposure difference Level (1-6 EV at 1.0 EV step), off)
- Photo Creativity : Yes (via iAuto Mode)
- Shooting Tips : Yes
- Sweep Panorama : Horizontal (Wide/Standard), Vertical, and 3D Panorama

Exposure System

- Picture Effect(s) : 11 types (15 variations): Posterization (Color, B/W), Pop Color, Retro Photo, Partial Color (R,G,B,Y), High Contrast Monochrome, Toy Camera, Soft High-key, Soft Focus, HDR Painting, Rich-tone Monochrome, Miniature
- Auto Exposure Lock : Yes (AE Lock with focus lock)
- Color Temperature : 2500 - 9900 k with 15-step Magenta / Green compensation
- Creative Style : Standard, Vivid, Portrait, Landscape, Sunset, B/W (Contrast (-3 to +3steps), Saturation(-3 to +3steps), Sharpness(-3 to +3steps))
- D-Range Optimizer : Yes: (Auto, Level, Off)

- Exposure Bracketing : Yes: (3 Continuous)
- Exposure Compensation : ±3.0 EV (in 0.3 EV steps)
- Exposure Settings : iAUTO, Program AE (P), Aperture priority (A), Shutter priority (S), Manual (M), Sweep Panorama (2D), 3D Sweep Panorama, Anti Motion Blur, Picture Effect, Scene Selection
- ISO : Auto (ISO 100-3200), Selectable (ISO 100 to 25600)
- Metering : Advanced 1200-zone evaluative metering
- Metering Modes : Multi-segment, Center-weighted, Spot
- Metering Sensitivity : 0EV-20EV, (at ISO 100 equivalent w/ f/2.8 lens)
- Noise Reduction : Long Exposure NR: (On/Off, available at shutter speeds longer than 1 second) High ISO NR: (High/Normal/Low)
- Scene Mode(s) : Portrait, Landscape, Macro, Sports action, Sunset, Night portrait, Night View, Handheld Twilight
- White Balance Mode : Auto,Daylight, Shade, Cloudy, Incandescent, Fluorescent, Flash, Setting the color temperature, Color Filter, Custom

Imaging Sensor

- Imaging Sensor : Exmor™ APS HD CMOS sensor (23.5 X 15.6mm)
- Processor : BIONZ™ image processor
- Anti Dust : Charge protection coating on Low-Pass Filter and electromagnetic vibration mechanism
- Pixel Gross : Approx. 16.7 megapixels
- Effective Picture Resolution : Approx. 16.1 megapixels
- Focal Length Conversion Factor : 1.5x
- Color Filter System : RGB primary color filters

Optics/Lens

- Lens Mount Type : Sony E-mount
- Aperture (Max.) : f/3.5-5.6
- Aperture (Min.) : f/22-34
- Focal Length (35mm equivalent) : 27mm-82.5mm (35mm equivalent)
- Lens Construction : Metal
- Lens Groups-Elements : 9 groups, 11 elements (4 aspheric surfaces)
- Minimum Focus Distance : 9.8" (0.25m)
- Angle of View : 76^o - 29^o
- Aperture Blade : 7 blades (Circular aperture)
- Aspheric Elements : (4 aspheric surfaces)
- Dimensions (Max. Diameter x Length) : 62 x 60mm
- Exterior Finish : Metal
- Internal Motor : Yes (Stepping motor)
- Lens Weight : 6.9 oz (194g)
- Maximum Magnification : 0.3x
- Steady Shot Mode:Active : Lens-based Image Stabilization

9.2. ADIS16488

FUNCTIONAL BLOCK DIAGRAM

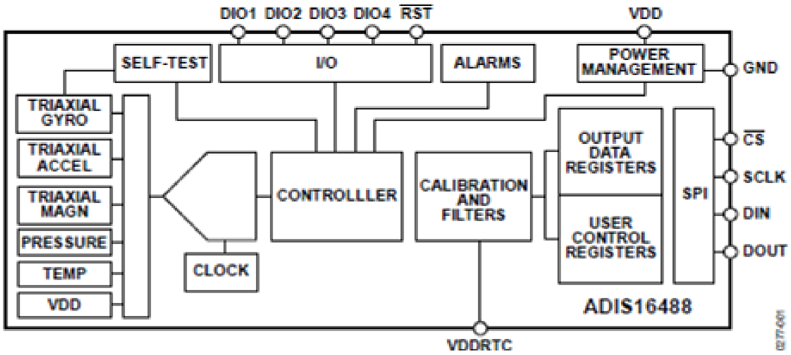


Fig. 9.1. ADIS functional block diagram

SPECIFICATIONS

T_A = 25°C, VDD = 3.3 V, angular rate = 0°/sec, dynamic range = ±450°/sec ± 1 *g*, 300 mbar to 1100 mbar, unless otherwise noted.

Table 1.

Parameter	Test Conditions/Comments	Min	Typ	Max	Unit
GYROSCOPES					
Dynamic Range		±450		±480	°/sec
Sensitivity	x_GYRO_OUT and x_GYRO_LOW (32-bit)		3.052×10^{-7}		°/sec/LSB
Initial Sensitivity Tolerance				±1	%
Sensitivity Temperature Coefficient	−40°C ≤ T_A ≤ +70°C, 1 σ		±35		ppm/°C
Misalignment	Axis-to-axis		±0.05		Degrees
	Axis-to-frame (package)		±1.0		Degrees
Nonlinearity	Best-fit straight line, FS = 450°/sec		0.01		% of FS
Initial Bias Error	1 σ		±0.2		°/sec
In-Run Bias Stability	1 σ		6.25		°/hr
Angular Random Walk	1 σ		0.3		°/√hr
Bias Temperature Coefficient	−40°C ≤ T_A ≤ +70°C, 1 σ		±0.0025		°/sec/°C
Linear Acceleration Effect on Bias	Any axis, 1 σ (CONFIG[7] = 1)		0.009		°/sec/*g*
Output Noise	No filtering		0.16		°/sec rms
Rate Noise Density	f = 25 Hz, no filtering		0.0066		°/sec/√Hz rms
3 dB Bandwidth			330		Hz
Sensor Resonant Frequency			18		kHz
ACCELEROMETERS	Each axis				
Dynamic Range		±18			*g*
Sensitivity	x_ACCL_OUT and x_ACCL_LOW (32-bit)		1.221×10^{-8}		*g*/LSB
Initial Sensitivity Tolerance				±0.5	%
Sensitivity Temperature Coefficient	−40°C ≤ T_A ≤ +85°C, 1 σ		±25		ppm/°C
Misalignment	Axis-to-axis		±0.035		Degrees
	Axis-to-frame (package)		±1.0		Degrees
Nonlinearity	Best-fit straight line, ±10 *g*		0.1		% of FS
	Best-fit straight line, ±18 *g*		0.5		% of FS
Initial Bias Error	1 σ		±16		m*g*
In-Run Bias Stability	1 σ		0.1		m*g*
Velocity Random Walk	1 σ		0.029		m/sec/√hr
Bias Temperature Coefficient	−40°C ≤ T_A ≤ +85°C		±0.1		m*g*/°C
Output Noise	No filtering		1.5		m*g* rms
Noise Density	f = 25 Hz, no filtering		0.067		m*g*/√Hz rms
3 dB Bandwidth			330		Hz
Sensor Resonant Frequency			5.5		kHz
MAGNETOMETER					
Dynamic Range		±2.5			gauss
Sensitivity			0.1		mgauss/LSB
Initial Sensitivity Tolerance				±2	%
Sensitivity Temperature Coefficient	1 σ		275		ppm/°C
Misalignment	Axis to axis		0.25		Degrees
	Axis to frame (package)		0.5		Degrees
Nonlinearity	Best fit straight line		0.5		% of FS
Initial Bias Error	0 gauss stimulus		±15		mgauss
Bias Temperature Coefficient	−40°C ≤ T_A ≤ +85°C, 1 σ		0.3		mgauss/°C
Output Noise	No filtering		0.45		mgauss
Noise Density	f = 25 Hz, no filtering		0.054		mgauss/√Hz
3 dB Bandwidth			330		Hz

ABSOLUTE MAXIMUM RATINGS

Table 3.

Parameter	Rating
Acceleration	
Any Axis, Unpowered	2000 *g*
Any Axis, Powered	2000 *g*
VDD to GND	−0.3 V to +3.6 V
Digital Input Voltage to GND	−0.3 V to VDD + 0.2 V
Digital Output Voltage to GND	−0.3 V to VDD + 0.2 V
Operating Temperature Range	−40°C to +85°C
Storage Temperature Range	−65°C to +150°C[1]
Barometric Pressure	6 bar

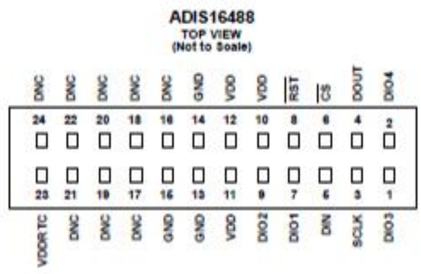
[1] Extended exposure to temperatures that are lower than −40°C or higher than +105°C can adversely affect the accuracy of the factory calibration.

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Table 4. Package Characteristics

Package Type	θ_{JA}	θ_{JC}	Device Weight
24-Lead Module (ML-24-6)	22.8°C/W	10.1°C/W	48 g

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS



NOTES
1. THIS REPRESENTATION DISPLAYS THE TOP VIEW PINOUT FOR THE MATING SOCKET CONNECTOR.
2. THE ACTUAL CONNECTOR PINS ARE NOT VISIBLE FROM THE TOP VIEW.
3. MATING CONNECTOR: SAMTEC CLM-112-02 OR EQUIVALENT.
4. DNC = DO NOT CONNECT TO THESE PINS.

Figure 5. Mating Connector Pin Assignments

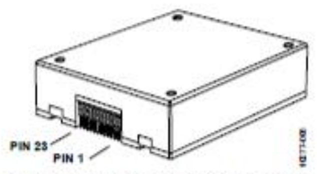


Figure 6. Axial Orientation (Top Side Facing Up)

Table 5. Pin Function Descriptions

Pin No.	Mnemonic	Type	Description
1	DIO3	Input/output	Configurable Digital Input/Output.
2	DIO4	Input/output	Configurable Digital Input/Output.
3	SCLK	Input	SPI Serial Clock.
4	DOUT	Output	SPI Data Output. Clocks output on SCLK falling edge.
5	DIN	Input	SPI Data Input. Clocks input on SCLK rising edge.
6	$\overline{CS}$	Input	SPI Chip Select.
7	DIO1	Input/output	Configurable Digital Input/Output.
8	$\overline{RST}$	Input	Reset.
9	DIO2	Input/output	Configurable Digital Input/Output.
10, 11, 12	VDD	Supply	Power Supply.
13, 14, 15	GND	Supply	Power Ground.
16 to 22, 24	DNC	Not applicable	Do Not Connect to These Pins.
23	VDDRTC	Supply	Real-Time Clock Power Supply.

Fig. 9.2. ADIS16488 pin configuration

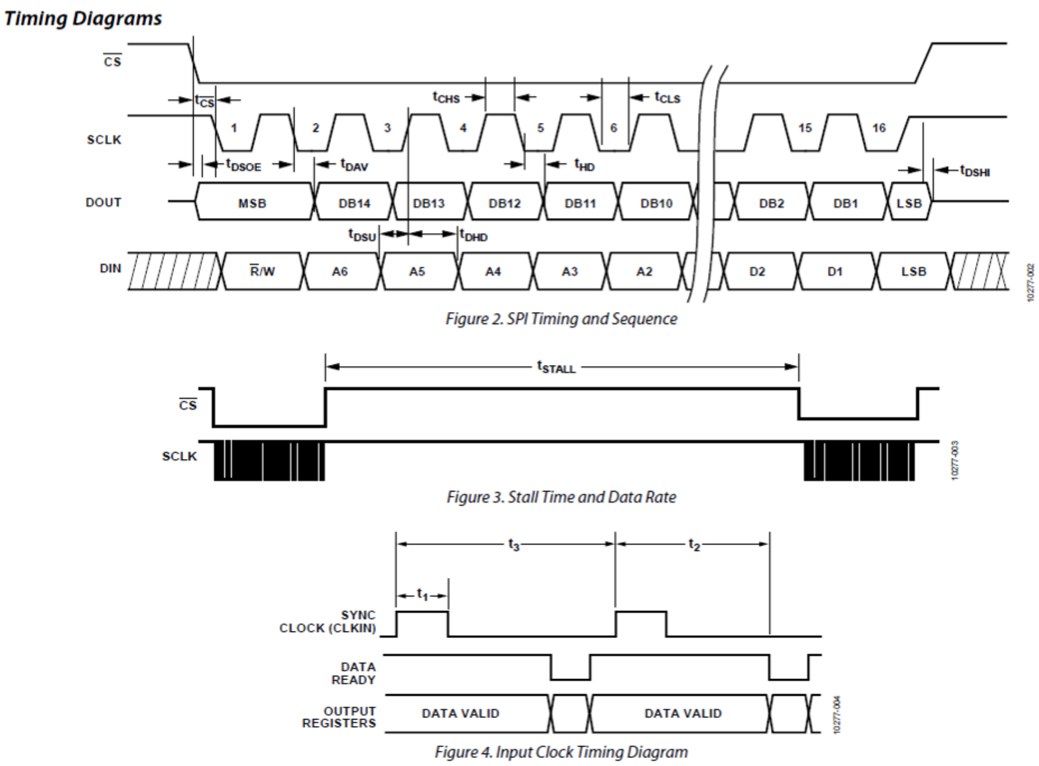


Fig. 9.3. SPI timing

9.3. Overo

Some extra specifications or valuable information about Overo:

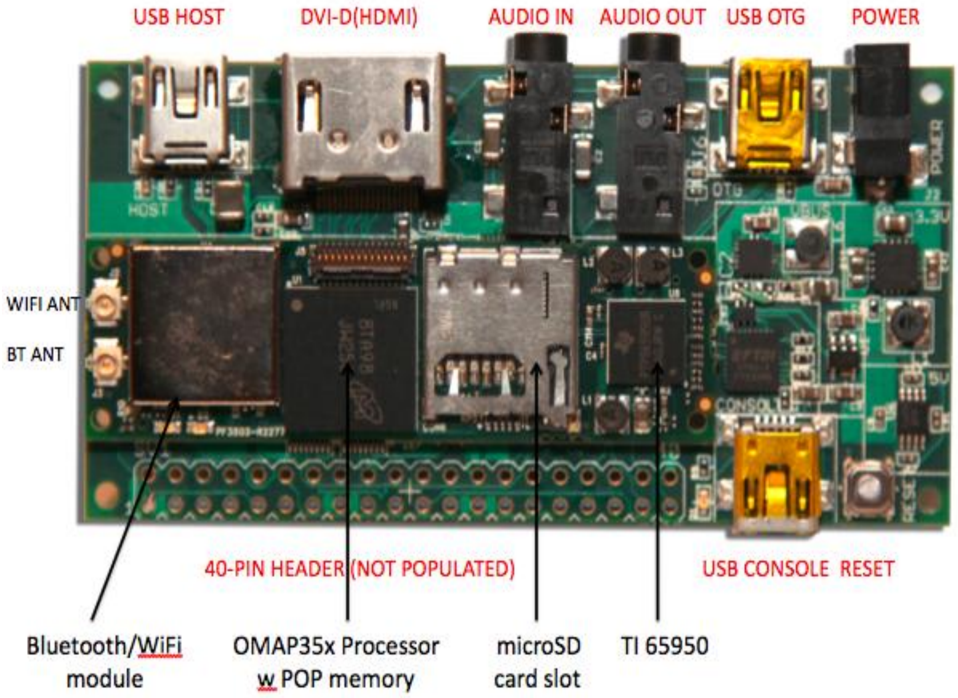


Fig. 9.4. Overo and Chestnut43 (old) interfaces

A 40-pin header, not populated, is available on several expansion boards of the Overo series.

- All logic levels are 1.8V.
- Signals available on 0.100" through-holes.
- A to D converter lines run direct to the TPS65950 with a maximum 2.5V.
- The VCC_1.8 signal is generated on the expansion board.
- The 40-pin header is available on the Summit, Tobi, Chestnut43, Palo43, Palo35 and Gallop43 expansion boards.
- This 40-pin header is not available on any Overo COM.

Table 9.1. 40-pin Overo header (pinout)

Signal	Pin	Pin	Signal
V_BATT	40	39	ADCIN4
ADCIN3	38	37	AGND
ADCIN5	36	35	ADCIN6
ADCIN2	34	33	ADCIN7
PWM1	32	31	PWM0
GPIO144_PWM9	30	29	GPIO147_PWM8
GPIO145_PWM10	28	27	GPIO146_PWM11
VCC_1.8	26	25	GND
GPIO185_SDA3	24	23	GPIO184_SCL3
GPIO166_IR_TXD3	22	21	GPIO165_IR_RXD3
GPIO163_IR_CTS3	20	19	GPIO170_HDQ_1WIRE
GPIO_10	18	17	GPIO_186
VCC_1.8	16	15	GND
POWERON	14	13	GPIO[0/31]_WAKEUP
VBACKUP	12	11	SYS_EN
GPIO148_TXD1	10	9	GPIO151_RXD1
GPIO175_SPI1_CS1	8	7	GPIO173_SPI1_MISO
GPIO174_SPI1_CS0	6	5	GPIO172_SPI1_MOSI
GPIO114_SPI1_NIRQ	4	3	GPIO171_SPI1_CLK
VCC_3.3	2	1	GND

9.4. GPIO configuration

An easy way to access to GPIO pins on Linux is by using the command:

root@overo: /sys/class/gpio

If a GPIO is not available, then it is necessary to export the desired GPIO ("*echo*" to write and "*cat*" to read, example for GPIO146):

echo 146 > export

Then, if GPIO is configured as an input:

echo in > /sys/class/gpio/gpio146/direction

Data read from this port is accessible through the command:

cat /sys/class/gpio/gpio146/value

9.5. PWM driver

PWM driver can be load with these commands:

insmod *.ko (default values).
insmod *.ko frequency=38000 timers=10 (specific PWM frequency and PWM).

To see which modules are loaded, execute command:

lsmod

If any problem occurs, to remove the driver (but sometimes this fails and system must be rebooting to work correctly):

rmmod *.ko

9.6. LN-200

For the project it is also important to evaluate its functionality and precision. For that reason, it is decided to work too with a more sophisticated device already prepared and used by GIN group.

It is the LN-200 and can be considered close to the top of available IMU (they are “professional” devices, not common) because of its performance and functionalities (it uses fiber optic). The LN-200 comprises three solid-state fiber optic gyros (FOG), and three solid state silicon Micro-electronic mechanical System (MEMS) accelerometers in a compact package. Digital output data of incremental velocity and incremental angle are provided to user equipment over a digital serial data bus.

Fig. 9.5. LN 200

Main features and specifications:

- Gyro Input Range: 1000 deg/sec
- Gyro Rate Bias: 1.0 deg/hr
- Gyro Rate Scale Factor: 100 ppm
- Angular Random Walk: 0.07 deg/√hr
- Accelerometer Range: 40 g
- Accelerometer Linearity: 150 ppm
- Accelerometer Scale Factor: 300 ppm
- Accelerometer Bias: 0.3 mg
- Dimensions: 168 x 195 x 146 mm
- Weight: 4.5 kg
- Power Consumption: 16 W (typical)
- Input Voltage: +12 to +28 V

SPAN™ | UIMU-LN200

Tactical Grade, Low Noise IMU Combines with NovAtel's GNSS Technology to Provide 3D Position, Velocity and Attitude Solution

Benefits

Low noise, low bias sensor excellent for airborne survey applications

Easy integration with NovAtel's SPAN capable GNSS/INS receivers

Features

Closed-loop fiber optic gyro technology

200 Hz data rate

12-28 VDC power input

SPAN INS functionality

SPAN: World-Leading GNSS + INS Technology

SPAN (Synchronous Position, Attitude and Navigation) technology brings together two different but complementary technologies: Global Navigation Satellite Systems (GNSS) positioning and inertial navigation. The absolute accuracy of GNSS positioning and the stability of Inertial Measurement Unit (IMU) gyro and accelerometer measurements are tightly coupled to provide an exceptional 3D navigation solution that is stable and continuously available, even through periods when satellite signals are blocked.

UIMU-LN200 Overview

The UIMU-LN200 contains the Northrop Grumman LN200 IMU. The LN200 is a tactical grade IMU containing closed-loop fiber optic gyros and solid-state silicon accelerometers. The UIMU-LN200 handles the power requirements of the IMU from a 12-28 V power input and provides the IMU data to a SPAN enabled GNSS/INS receiver such as the FlexPak6™ or SPAN-SE using a custom NovAtel interface. The GNSS/INS receiver uses IMU measurements to compute a blended GNSS/INS position, velocity and attitude solution at up to 200 Hz. The LN200 is ITAR controlled and requires export approval for customers outside the United States.

Advantages of UIMU-LN200

Low noise and stable accelerometer and gyro sensor biases make the UIMU-LN200 an ideal choice for airborne mapping applications. IMU mounting is made easy by its small footprint. The UIMU-LN200 is available as a complete assembly, including the IMU and environmentally sealed enclosure. Also, customers who already have the LN200 IMU can purchase the enclosure separately and easily integrate the IMU.

SPAN™ | UIMU-LN200

SPAN System Performance[1]

Horizontal Position Accuracy (RMS)	
Single Point L1	1.5 m
Single Point L1/L2	1.2 m
SBAS	0.6 m
DGPS	0.4 m
L-Band	
VBS	0.6 m
XP	0.15 m
HP	0.1 m
RT-2™	1 cm+1 ppm
Acceleration Accuracy[2]	0.03 m/s^2 RMS
Max Velocity[3]	515 m/s
Data Rate	
IMU Measurements	200 Hz
INS Position	200 Hz
INS Velocity	200 Hz
INS Attitude	200 Hz

IMU Performance

UIMU-LN200	
Gyro Input Range	±1000 deg/sec
Gyro Rate Bias	1.0 deg/hr
Gyro Rate Scale Factor	100 ppm
Angular Random Walk	0.07 deg/√hr
Accelerometer Range[4]	±40 g
Accelerometer Linearity	150 ppm
Accelerometer Scale Factor	300 ppm
Accelerometer Bias	0.3 mg
UIMU-LN200-L	
Gyro Input Range	±1000 deg/sec
Gyro Rate Bias	1.0 deg/hr
Gyro Rate Scale Factor	100 ppm
Angular Random Walk	0.07 deg/√hr
Accelerometer Range[4]	±40 g
Accelerometer Linearity	500 ppm
Accelerometer Scale Factor	1000 ppm
Accelerometer Bias	1.5mg

IMU Physical and Electrical

Dimensions	168 x 195 x 146 mm
Weight	4.5 kg
Power	
Power Consumption	16 W (typical)
Input Voltage	+12 to +28 V
Connectors	
Power	MIL-C-38999-III, 3 pin
Communication	MIL-C-38999-III, 13 pin

Environmental

Temperature	
Operating	-30°C to +60°C
Storage	-45°C to +80°C
Humidity	95% non-condensing
MTBF	20,000 hrs
Waterproof	IEC 60259 IPX7
Dust	IEC 60259 IP6X

Optional Accessories

- Inertial Explorer post-processing software

Performance During GNSS Outages[1, 5]

Outage Duration	Positioning Mode	Position Accuracy (m) RMS		Velocity Accuracy (m/s) RMS		Attitude Accuracy (degrees)[2] RMS		
		Horizontal	Vertical	Horizontal	Vertical	Roll	Pitch	Heading
0s	RTK	0.020	0.050	0.020	0.010	0.010	0.010	0.020
	HP	0.100	0.080	0.020	0.010	0.010	0.010	0.020
	SP	1.200	0.600	0.020	0.010	0.011	0.011	0.022
	PP[6]	0.010	0.015	0.020	0.010	0.005	0.005	0.008
10 s	RTK	0.120	0.070	0.025	0.011	0.011	0.011	0.022
	HP	0.390	0.320	0.030	0.012	0.012	0.012	0.030
	SP	1.340	0.670	0.030	0.012	0.012	0.012	0.029
	PP[6]	0.020	0.020	0.010	0.010	0.005	0.005	0.008
60 s	RTK	2.790	0.630	0.102	0.023	0.013	0.013	0.031
	HP	3.120	0.760	0.105	0.019	0.013	0.013	0.040
	SP	3.510	0.960	0.105	0.019	0.015	0.015	0.039
	PP[6]	0.110	0.030	0.020	0.015	0.008	0.008	0.010

NovAtel

Version 8 - Specifications subject to change without notice.

Printed in Canada. D10151

UIMU-LN200 July 2012

For the most recent details of this product:
novatel.com/assets/Documents/Papers/LN200.pdf

[1] Typical values. Performance specifications subject to GPS system characteristics, US DOD operational degradation, ionospheric and tropospheric conditions, satellite geometry, baseline length, multipath effects and the presence of intentional or unintentional interference sources.
[2] When SPAN is in RTK mode.
[3] Export licensing restricts operation to a maximum of 515 metres per second.
[4] GNSS receiver sustains tracking up to 4 g.
[5] Steady state and outage performance remains the same for the -L model.
[6] Post-processing results using Inertial Explorer software.