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Optimal Positioning Solutions in Remote Sensing Technologies for Structural Health Monitoring

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Nella vita non c'è nulla da temere, solo da capire.
Margherita Hack

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Abstract

Structural Health Monitoring (SHM) is the process of implementing a strategy for damage detection of structures and infrastructures, with several application to aerospace, civil or mechanical engineering. An important activity for SHM is the so-called Optimal Sensor Placement (OSP), that aims to customize the monitoring sensing system over a target structure: it allows to maximise the spatial resolution of the detected quantities, e.g. the mode shapes, especially when a limited number of sensors is available to cover a spatially extended structure such as civil or aerospace systems.

In this framework, an interesting and beneficial approach appears to be a multidisciplinary one, which aims to apply Remote Sensing (RS) data to OSP.

Typically, OSP strategies are based on preliminary Finite Element (FE) models of the target system, which provide an estimate of the mode shapes from which the most informative points can be drawn. This approach presents some issues as FE models are based on surveys and on preliminary geometric and local mechanical information of the different structural elements. This thesis explores the strategy of using RS data for OSP, examining the potential of different platforms for the placement of measuring instruments. In this approach, FE models could be replaced directly by real data, such as position and displacement (or speed or acceleration) of points of the actual structure.

In this thesis, guidelines are proposed for the choice of the best platform and remote technological solution based on specific technical-economical requirements for remote OSP.

Introduction

In today's interconnected world, structures and infrastructures are complex engineering systems essential to society. In particular, their dependence on humanity is so important and pressing that such systems need to be safer and more reliable. Therefore, the need of monitoring and evaluating the health of structures arises and it is necessary to implement a strategy for damage detection called Structural Health Monitoring (SHM): it mainly exploits sensors for the collection of data and, in general, the more sensors are placed on the monitored structure, the more detailed information can be obtained to depict the structural health status. However, sensors can be placed only in a finite number of locations and the number of sensors is limited due to issues such as, structural inaccessibility, budget constraints, etc. Therefore, given this limitation, sensors locations have to be optimized to obtain as much structural information as possible, through Optimal Sensor Placement (OSP). OSP allows to identify the optimal positions of sensors, maximizing the spatial resolution of the detected quantities, especially when a limited number of sensors is available to cover a spatially extended structure such as civil or aerospace systems. Typical OSP strategies present several issues: virtualization-based strategy can be altered by model geometric and mechanical discrepancy errors, while real-data strategy, that estimates structural properties from records of dynamic data obtained by dedicated sensors mounted on the structure, has several challenges such as problems of accessibility, difficulties in dynamic identification and issue with direction of acquisition.
In this thesis work, the author explores the possibility of using remote sensing platforms to collect data to be used as input for the Optimal Sensor Placement. In fact, Remote Sensing (RS) allows the acquisition of information on Earth through instruments not in direct contact with the surface or feature, often mounted on board a satellite or an aircraft. These on-board instruments are sensors capable of collecting information in the entire electromagnetic spectrum. Due to its characteristics, Remote Sensing potentially lends itself to collect data to be used as input for OSP, such as position and displacement together with their variation over time. Therefore, it is necessary to define the best methodology to remotely collect data,

preventing all the aforementioned problems, and use the data collected subsequently for OSP, avoiding the employment of the model and its related uncertainties.
The author decided to structure her thesis in the following way:

- In Chapter 1, the state of the art of RS principles and technology is illustrated;
- In Chapter 2, OSP requirements have been identified and the methodology for the selection process is presented, based on Analytical Hierarchy Process;
- In Chapter 3, the state of the art of RS platform is shown and the selection of the most suitable one is carried out, pointing out that the Unmanned Air Vehicle (UAV) should be chosen;
- In Chapter 4, a general overview of UAV is described, together with possible configuration suitable for OSP from literature.
- In Chapter 5, conclusions are drawn, underling that remote sensing appear to be a proper tool to collect data for OSP purposes and the author suggests possible future steps to validate the UAV solution.

Chapter 1

A general overview of Remote Sensing

1.1 Introduction

Remote sensing (RS) is the science that allows to obtain qualitative and quantitative information on the environment and on objects placed at a distance from a sensor by means of electromagnetic radiation measurements (emitted, reflected or transmitted) which interacts with the physical surfaces of interest.
Remote sensing technologies find their application where it is necessary to widen information that can be acquired on the ground, allowing to investigate a wider area and limiting the use of time and resources.
Furthermore, remote sensing allows to acquire data of several areas, even dangerous environments or not reachable from ground.
Obviously, each remote sensing technology has both advantages and disadvantages, affecting technological, operational and economic aspects.
The determination of the optimal choice is not exclusive but it must be evaluated on the basis of costs depending on the actual application and the case specific characteristics.

In this chapter, the author aims to lay the foundations to better understand the concept of remote sensing in order to make more conscious and complete choices, through an explanation of the basic characteristics of electromagnetic energy, its source and the electromagnetic spectrum, together with an illustration of the basic principles of remote sensing and a description of the types of data that can be acquired through remote sensing systems.

1.2 Electromagnetic energy

Electromagnetic energy is the means by which information is transmitted from the target to the sensor [1]. In fact, the information can be encoded in the different characteristics of the electromagnetic wave, or in its frequency content, its intensity or its polarization. Therefore, this information is propagated by electromagnetic radiation directly through the free space at the speed of light or indirectly by reflection, rarefaction, scattering.
It is important to underline that electromagnetic waves interact with surfaces and atmosphere, and this interaction strongly depends on the waves' frequency.

1.2.1 An overview of electromagnetic waves

Electromagnetic waves are waves created as a result of vibrations (or periodic change) between an electric field and a magnetic field, and, on the basis of how this periodic change takes place and the power generated, different wavelengths of electromagnetic spectrum are produced.
In vacuum, electromagnetic waves travel at a constant velocity, approximately the speed of light, of $c = 300000 \ \ km/s$, and they can propagate or travel through anything, as there is no need for a medium. In presence of an homogeneous isotropic medium, a transverse wave is formed, because the electric and magnetic fields' oscillations are perpendicular to each other and they are also perpendicular to the direction of energy and wave propagation.

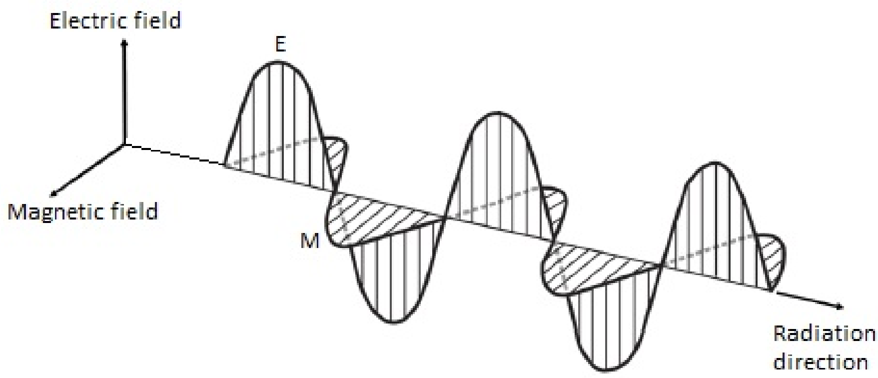

Figure 1.1. Electromagnetic radiation: two oscillation components

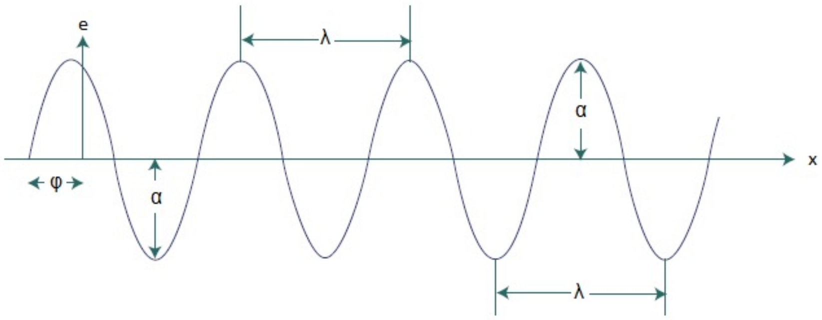

Figure 1.2. Electromagnetic radiation: characteristics of a wave

Considering a sine wave, as shown in Figure 1.2, it can be characterized by three main parameters:

- *Wavelength* λ: it is the distance travelled by the energy from the electrical energy maximum until reaching again the maximum, or any other corresponding states of energy. In other word, λ is the length of one oscillation cycle and it is usually measured in micrometers $[\mu m]$.
- *Amplitude* α: it is the value of wave peak. This characteristic is important as the larger α the higher the wave energy, and, especially in active sensors, the amplitude of the signal is used to measure the intensity.
- *Phase* ϕ: it expresses the fraction the start point differs from the distance origin and it is an important quantity, in particular for precise ranging.

Moreover, the amount of time for an electromagnetic wave to complete one cycle is defined by the *period* and its reciprocal is the so-called *frequency*, that is the number of wave cycles in a second. To better understand the difference between the wavelength and the period, reference to Figure 1.3: the main difference between wavelength and period is that wavelength is the shortest distance between two successive points on a wave that are in phase while period is the time it takes for a full oscillation to occur at a given point.

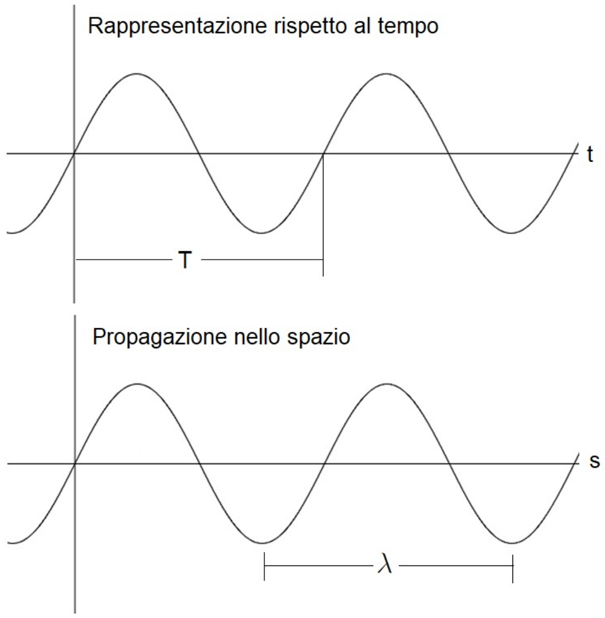

Figure 1.3.

The main source of electromagnetic energy is, of course, the Sun, but it is not the only as electromagnetic energy can be emitted by molecular agitation when the matter has an absolute temperature above zero.

1.2.2 Electromagnetic spectrum

Electromagnetic radiation can be classified by wavelength and the total wavelengths range is the so-called electromagnetic spectrum. Different portions of the spectrum correspond to different types of radiation: radio waves, microwave, infrared radiation, visible radiation, ultraviolet radiation, x-rays and gamma rays.

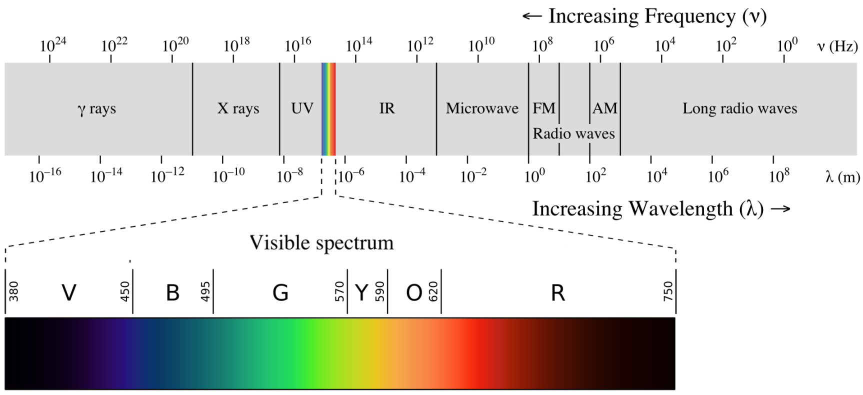

Figure 1.4. Electromagnetic spectrum By Philip Ronan- Gringer

As prior said, the behavior of radiation and its interaction with matter depends on its frequency, and accordingly changes. In fact, higher frequencies have shorter wavelengths (higher energy photons), while lower frequencies have longer wavelengths.

Therefore, different portions of the spectrum mean, as regards the observation of the earth, both different types of obtainable information and different volume of data that can be acquired.

Region	Wavelength	Typical Application
Gamma ray	<0.03 nanometer	Entirely absorbed by the Earth's atmosphere. Not available for remote sensing.
X-ray	0.03 to 30 nanometer	Entirely absorbed by the Earth's atmosphere. Not available for remote sensing.
Ultraviolet	0.03 to 0.4 micrometer	Wavelengths from 0.03 to 0.3 μm absorbed by ozone.
Photographic Ultraviolet	0.3 to 0.4 micrometer	Available for remote sensing. Can be imaged with cameras and sensors.
Visible	0.4 to 0.7 micrometer	Available for remote sensing. Can be imaged with cameras and sensors.
Near and Mid Infrared	0.7 to 3.0 micrometer	Available for remote sensing. Can be imaged with cameras and sensors.
Thermal Infrared	<0.7 to 3.0 micrometer	Available for remote sensing. Sensors are used for this wavelength.
Microwave or Radar	0.1 to 100 centimeter	Sensors that actively emit microwaves are used.
Radio	>100 centimeter	Not normally used for remote sensing.

Table 1.1. Major regions of the electromagnetic spectrum

1.2.3 Interactions with the atmosphere and with Earth's surface

For remote sensing application, it is important to remind that the Sun's energy has different interactions both with the atmosphere and the Earth's surface.

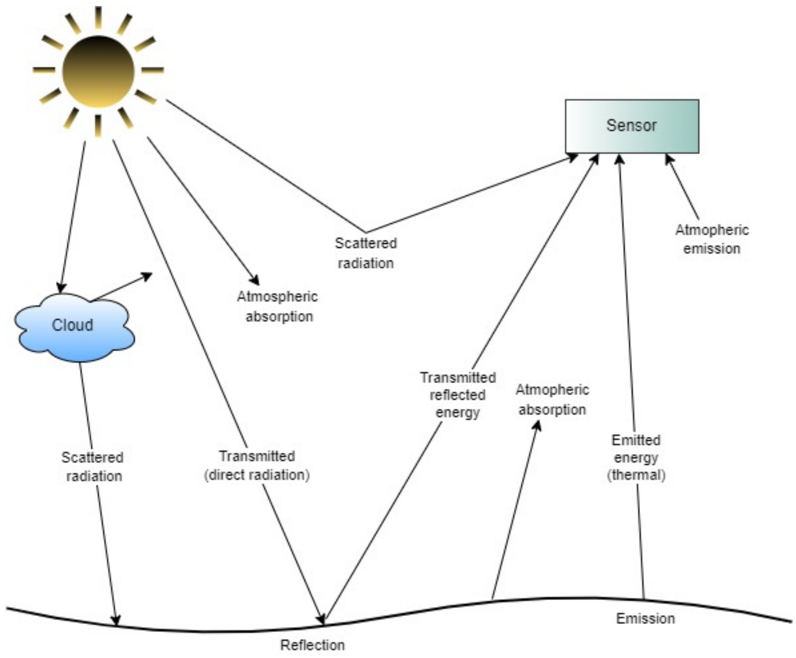

Figure 1.5. Electromagnetic energy interactions

Absorption and transmission

When the electromagnetic energy travels through the atmosphere, it is partially absorbed by several different molecules, among which the most absorbing in the atmosphere are carbon dioxide (CO_2), water vapour (H_2O) and ozone (O_3).
Moreover, atmospheric transmission is important because, as shown in figure 1.6, some wavelengths are not useful for all the applications, such as the remote sensing of the Earth's surface, due to the fact that the corresponding energy cannot penetrate through the atmosphere.

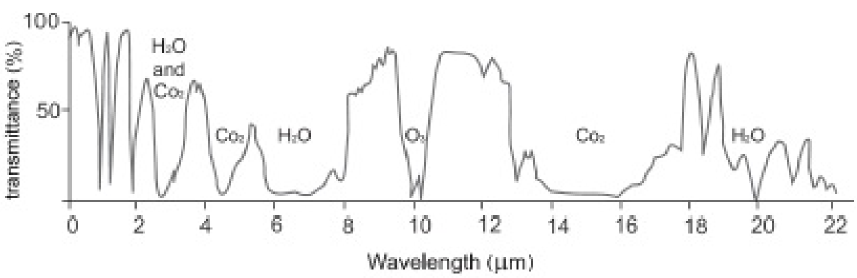

Figure 1.6. Atmospheric transmittance [2]

Only the portions of the spectrum outside the ranges of atmospheric gases' absorption can be used for remote sensing. The useful ranges are called the *atmospheric transmission windows* [2] and they consist of the following:

- 0.4 to 2 μm: in this range (visible, near infra-red, short-wavelength infrared), the radiation is mostly reflected energy. Remote sensors working in this range are usually named optical sensors, because this type of radiation follows the optics laws.

- 3 to 5 μm: 2 narrow windows in the thermal infrared; 8 to 14 μm: a broad window in the thermal infrared.

Due to atmospheric moisture, longer wavelengths show a strong absorption.
Besides, in the range between 22 μm to 1 mm, there is almost no transmission of energy.

Atmospheric scattering

Atmospheric scattering takes place when the particles/molecules in the atmosphere redirect the electromagnetic radiation from the original path.
There are several factors that determine the amount of scattering, in particular the radiation's wavelength, the amount of particles/molecules, and the distance traveled by the energy in the atmosphere. Depending on the size of the atmospheric particles, three types of scattering can be distinguished:

- *Rayleigh scattering*: it occurs when particles smaller than light wavelength interact with the electromagnetic radiation, thus this type of scattering is maximum for shorter wavelength.
  Rayleigh scattering interferes with remote sensors operating in the range of visible light from high altitudes. As compared to measurements taken on ground, shorter wavelengths are overestimated, because Rayleigh scattering generates a distortion of the characteristics of the reflected light.

- *Mie scattering*: it dominates where the wavelength is comparable in size to the atmospheric particles, and this type of scattering is mainly caused by the presence of aerosols, a mix of gas, water vapor and dust.
  Hence, Mie scattering occurs mainly in the lower atmosphere, where there is the presence of larger particles that dominate; consequently the most influenced spectral range is from the near ultraviolet to the middle infrared, affecting longer wavelengths radiation.

- *Non-selective scattering*: in the latter case, it occurs when the size of particles is larger than the radiation wavelength. Water droplets and large dust particles (i.g. clouds) are the main responsible for this effect, thus a remote sensor encounters some difficulties to operate through this environment and clouds limit the capability and operation of optical remote sensors.

Energy interactions with ground

In some remote sensing applications (land survey, vegetation control etc), the reflected electromagnetic energy is of particular importance, because it allows to gather information of the surface characteristics.
Reflection takes place when energy bounces off the target and, as a consequence, it is redirected; however not all the radiation is reflected as it can also be partially absorbed and/or transmitted, depending on the wavelength and the type of material.
There are two main types of reflection [2], representing the extremes of how the energy is reflected by the target, as shown in figure 1.7:

- *Specular reflection*: it occurs when the surface of impact is smooth and all the energy is reflected back in only one direction. This reflection results in a bright spot in the image, called hot spot.
- *Diffuse reflection*: it occurs when the surface is rough resulting in energy reflected uniformly in all directions.

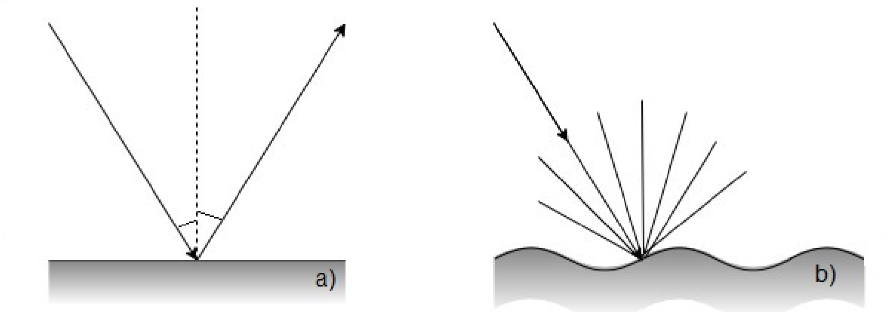

Figure 1.7. Specular a) and Diffuse b) reflection

The type of reflection depends on the roughness of the surface which is in turn linked to the wavelength of the incident radiation.

1.3 Remote Sensing Principles

As already mentioned above, remote sensing allows the acquisition of information on Earth through instruments not in direct contact with the surface or feature, often mounted on board a satellite or an aircraft. These on-board instruments are sensors capable of collecting information in the entire electromagnetic spectrum.
Each remote sensing technology involves the interaction with the radiation incident

on the target: therefore, this incident radiation is altered according to the physical properties of the target itself and, subsequently, it is reflected back and recorded by the sensor. If imaging systems are used, as shown in fig.1.8, it is called optical remote sensing, while when remote sensing involves the sensing of the emitted energy and the use of non-imaging sensors, it is referred to as thermal remote sensing.

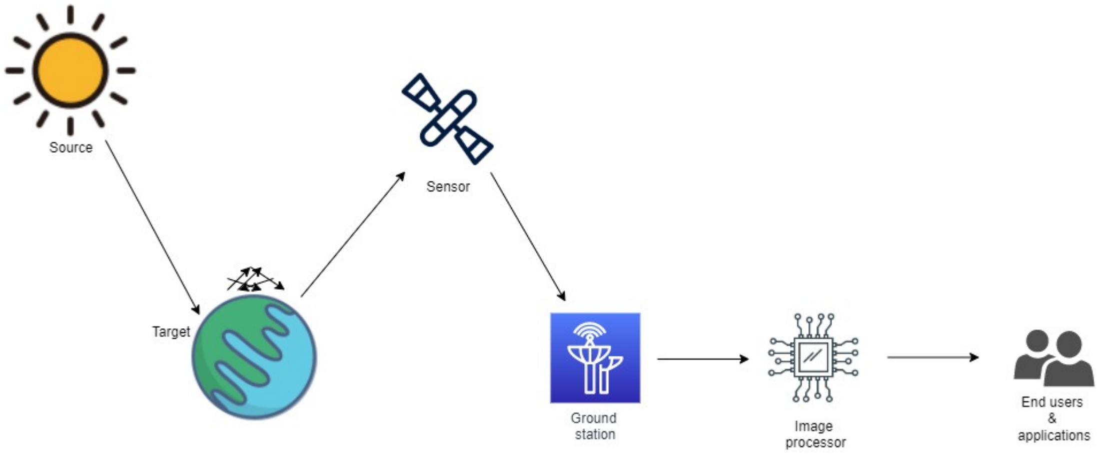

Figure 1.8. Remote sensing

The remote sensing technique is characterized by seven basic elements [3], with reference to fig.1.8:

A) Energy source or illumination - The first requirement is to have an energy source that illuminates the target of interest. This energy is in the form of electromagnetic radiation.

B) Radiation and the atmosphere - As the energy propagates from its source to the target, it comes into contact with and interacts with the atmosphere as it passes through.

C) Interaction with the target - The radiation, that manages to pass through the atmosphere, reaches and interacts with the target. The interaction between radiation and target depends on the characteristics of both.

D) Recording of energy by the sensor - At this point, a sensor (remote, not in contact with the target) is required to collect and record the electromagnetic radiation, scattered or emitted by the target.

E) Transmission, reception and processing - The energy received and recorded by the sensor need to be transmitted to a receiving and processing station, mostly in electronic form. There, in this station, the data are processed into an image, as hardcopy and/or digital copy.

F) Interpretation and analysis - The processed image has to be interpreted (visually, digitally or electronically) to extract information about the target.

G) End users and application - Finally, as useful information is brought out from the imagery, it reveals some new information or assists a user in solving a particular problem. The application of remote sensing is extensive, from environmental monitoring to land use, to ocean and wetland studies, to defense and military surveillance, to broadcasting and telecommunication.

1.4 Types of Remote Sensing Data

When acquiring remote sensing data, the data type is observed to depend both on the type of information and on the size and dynamics of the studied target.
The table below shows the different types of needed information and their associated sensors [1].

Type of needed information	**Type of sensor**
High spatial resolution and wide coverage	Imaging sensors, cameras
High spectral resolution over limited areas or along track lines	Spectrometers, spectroradiometers
Limited spectral resolution with high spatial resolution	Multispectral mappers
High spectral and spatial resolution	Imaging spectrometer
High-accuracy intensity measurement along line tracks or wide swath	Radiometers, scatterometers
High-accuracy intensity measurement with moderate imaging resolution and wide coverage	Imaging radiometers
High-accuracy measurement of location and profile	Altimeters, sounders
Three-dimensional topographic mapping	Scanning altimeters and interferometers

Table 1.2. Types of remote sensing data

The type of information can be divided into the following domains: spectral, spatial and temporal, and each domain has a relevant resolution associated with the requested information, or rather the level of detail at which the data are measured.

1.4.1 Spectral domain

The electromagnetic spectrum is characterized by several wavelengths, which are detected by the remote sensing instruments: the sensor measures a wavelength interval, a 'band' or 'channel. Some instruments are able to detect several bands, with relatively narrow wavelength widths, whereas others sense fewer broader bands. Most of the sensors are multi-spectral, meaning they detect more than one band: multi-spectral images provides the ability to differentiate objects that otherwise cannot be resolved by differences in texture or shape. This type of sensor has less than 70 bands with bandwidth of the order of micrometers.
Recently, hyper-spectral sensors have been developed: they have more than 100 bands and they are able to detect and record data in a narrow spectral band with nanometer bandwidth.

1.4.2 Spatial domain

Spatial resolution [1] is by definition the smallest area sampled or viewed by a sensor's detectors. In fact, objects, that are much smaller than the spatial resolution of the sensor, cannot be distinctly differentiated, thus, in order to observe more details/information, the resolution dimension should be smaller ('higher' or 'finer' resolution).
For instance, the spatial resolution of many instruments mounted on satellites varies between tens of meters to a few kilometers, among which military satellites have a higher spatial resolution but the data is often classified and not fully available.

Considering a digital image, we observe that a scene is created displaying data as picture elements, pixel, and spectral and spatial attributes are associated with each pixel.
The spectral information is the value assigned to each pixel via a numerical representation of the intensity measured by a sensor in a specific spectral band, while the spatial information includes the location of each pixel in an image and the apparent size of the resolution cell, hence the area on ground represented by each pixel.

[1] Spatial resolution and spatial scale are often confused, they are associated but not the same: the scale of an image is the ratio of the distance between two points on image to the geographic distance between the same points on ground.

1.4.3 Temporal domain

When analyzing remote sensing data, it is important to take into account the time of day or year at which an image was taken. This means choosing the image with awareness, for example selecting one shot in spring rather than in autumn or during daylight rather than at night.
Furthermore, knowing the date and time of the image is of particular relevance, as it can provide valuable additional information about evolution of phenomena.
If the main task is monitoring different processes or studying environmental changes, we use multitemporal imagery, also known as time series, which is imagery acquired at different times.

1.5 Remote sensing sensors

1.5.1 Intensity-based optical sensors

Intensity-based sensors are one of the first and simplest optical method to be used to measure distance: it consists of a light source and a detector.
These sensors typically employ optical fibers to transmit the light from source to object and then the light is reflected onto the detector.

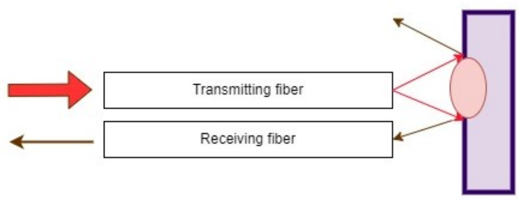

Figure 1.9. An example of fiber optical intensity sensor for distance measurements

Commonly, an intensity-based sensor response is characterized by zero signals at zero distance and at large distances and by an intensity peak at a specific distance, near the fiber tips [4].
This kind of sensor has the following main advantages/attraction:

- ✓ Simplicity and low cost;
- ✓ Ability to measure distance at a fast repetition rate, up to 100 KHz.
- ✓ Available for various probing distance, range from millimeters to centimeter;

On the other hand, these sensors have some limitations:

× Pre-calibration of all target objects is needed;

× Changes in the signal intensity (i.e. illumination intensity variations, optical connection losses, etc.) will be interpreted as changes in distance, because distance is derived from measured intensity of the signal.

× The signal can be sensitive to target object's tilt.

1.5.2 Triangulation sensors

Triangulation is a procedure that allows to determine distance or position from geometrical consideration of similar triangles [4].

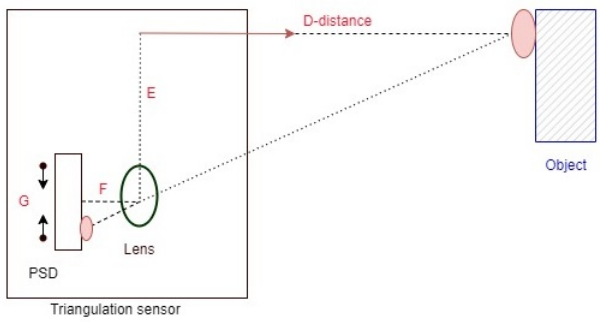

Figure 1.10. Optical triangulation sensor

As a source of illumination, a collimate laser is used to lighten the object. Afterward the lens optics of the camera is displaced from the laser source to image the spot of the laser on the object into a detector (position-sensitive). The figure 1.10 shows how the distance can be determined through similar triangles. The main attractions to these sensors are:

✓ Low cost;

✓ Ability to measure distance at a fast repetition rate, from 10 to 100 KHz;

On the other hand, there are some limitations:

× Not working on transparent object;

× The distance resolution of the sensor depends on the laser beam size, the detection pixel size and the distance;

× Angular geometry imposes a minimum and maximum sensing distance.

1.5.3 Time-of-Flight sensors

Time-of-Flight is an other common method for distance measurement: to find the distance, electromagnetic waves are sent to the object and the time taken for the waves to travel and come back is measured [4]. Hence, the distance is given by the time of flight in one way multiplied by the light speed.

Typically, laser time-of-flight sensors work sending a short pulse of light (nanoseconds) to the object . If the object is placed at a distance grater than 50 m, the time-of-flight can be measured by rather simple electronics and detectors; while at distances shorter than 10 m, temporal pulse shape has to be taken into account to measure the time delay between input peaks and returned pulses.

1.5.4 Confocal sensors

An other class of optical sensor is confocal sensor that can typically be applicable for accurate displacement measurements and millimeter surface profiles.
The principle at the base of confocal sensing is the use of the same optics to focus light on the object from an aperture and to detect the scattered back light. The signal varies strongly with the position of the object, allowing a displacement tracking with sub-micrometer accuracy.

1.5.5 Cameras in visible spectrum

Cameras are systems widely used for remote sensing applications, operating in the visible spectrum (400-700 nm): visible light is collected and converted into an electrical signal, to subsequently organize this information and produce images and videos.
Visible cameras are designed to create images that replicate human vision, capturing light in red, green, and blue (RGB) wavelengths for accurate color representation. In addition, modern technologies allow for HD resolution or higher and there may be different lens options for wide angle or telephoto views to identify objectives and objects in the scene.
Since these instruments work in the visible spectrum, they need light in order to operate. In fact, their performance is greatly reduced by adverse flight and atmospheric conditions such as fog, haze, smoke, heat waves and smog, but also engines that produce high frequencies and vibrations.
Depending on the specific application, different types or combinations of cameras can be mounted on board the drone. If, for example, the mission plans to cover large areas of vision, adequate systems must be used, such as omnidirectional vision

systems. In fact, omnidirectional systems are suitable for surveillance applications. If, on the other hand, you want to do 3D modeling, you can build a system consisting of four cameras to be able to model in 3D through triangulation starting from superimposed images, which are taken at different angles of view.

1.5.6 Thermal Infrared Sensors

An infrared thermal sensor (TIR) detects radiant energy, based on the assumption that objects with temperatures above absolute zero put infrared radiation as a function of temperature and wavelength.
According to ISO 20473 [5], the wavelengths of the spectral bands vary as follows:

- Near-Infrared (NIR): 0.78 µm - 3 µm,
- Middle-Infrared: 3 µm - 50 µm,
- Far-Infrared: 50 µm -1000 µm.

TIR radiation refers to electromagnetic waves with a wavelength between 3.5 and 20 µm.
In general,TIR sensors are a powerful tool for collecting, analyzing and modeling energy flows and temperature changes. Some typical examples of TIR-type remote sensing applications include imaging of vegetation reflectance and temperature; the parameterization of soil surface humidity conditions; simulations of the energy exchange of the environment on spatial and temporal scales; the inference of the surface water content of the soil and fractional vegetation cover; the determination of evapotranspiration in vegetated areas; evaluation of the urban heat island effect.
There are two varieties of thermal imaging systems: cooled and uncooled. Cooled cooled TIR cameras provide sensitivity and resolution improvements. The uncooled TIR chambers are characterized by low cost, small size and low power consumption applications.

1.5.7 Synthetic Aperture Radar

Synthetic aperture radar (SAR) is an imaging radar moving in a straight line, that can be mounted either on an airplane or on a spacecraft orbiting in space [6].
If on one hand optical imagery is analogous to interpreting a photograph, on the other hand the principle behind SAR is a system of electromagnetic waves emission towards a surface and the consequent collection of the signal echoed back or back-scattered together with the time delay: the signal is, in fact, responsive to the characteristics of the surface such as structure, humidity, composition etc.

The image of the detected region is obtained by distributing the averaged values of the electromagnetic wave reflected from the surface (modulus and phase) on the sampling areas. In this way, a pixelated image is obtained, typically in black and white. The clearer the sample, the higher the module of the reflected wave is.

SAR techniques exploit the synthesis of a virtual 10-km-long antenna from a 10-m-long real physical antenna in the direction of flight, thanks to the fact that the radar is moving following its orbit. Thus, while moving, the radar sweeps the footprint of the antenna on ground repeatedly transmitting pulses and receiving returned pulses echoes, and it scans every point on the terrain many times along the path.

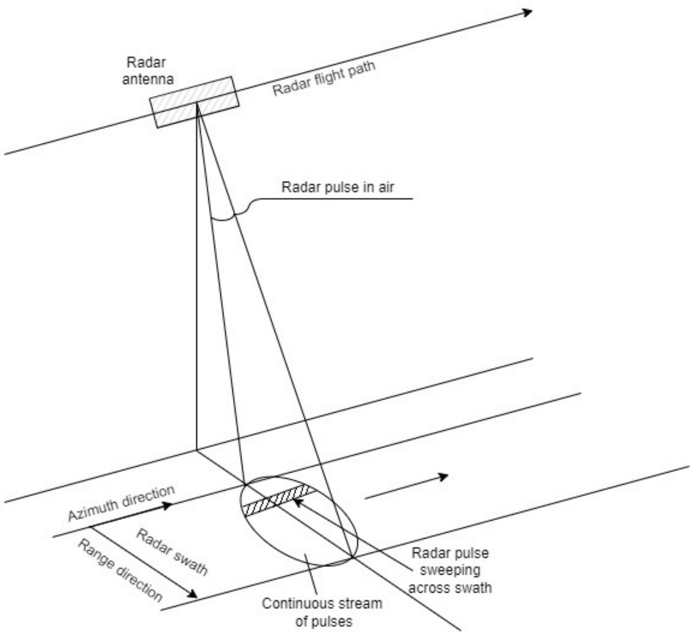

Figure 1.11. SAR

While the radar passes, the distance between the radar and a specific point changes in a constantly and predictably way and the change in distance is accurately encoded in the phase of received pulse (phase history). In order to create a synthetic aperture, the signal is focused through computer processing, compensating each pulse phase history for a point: this results in an image resolution that can be improved up to an ideal one-half of the antenna's diameter.

While optical sensors collect data in the visible, near-infrared and infrared electromagnetic spectrum, SAR works in longer wavelength at centimeter to meter scale, often known as bands. The table 1.3 shows the different bands with their associated frequency, wavelength and typical applications.

Band	Frequency	Wavelength	Typical Application
Ka	27–40 GHz	1.1–0.8 cm	Rarely used for SAR (airport surveillance)
K	18–27 GHz	1.7–1.1 cm	Rarely used (H2O absorption)
Ku	12–18 GHz	2.4–1.7 cm	Rarely used for SAR (satellite altimetry)
X	8–12 GHz	3.8–2.4 cm	High resolution SAR (urban monitoring; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4–8 GHz	7.5–3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2–4 GHz	15–7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1–2 GHz	30–15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3–1 GHz	100–30 cm	Biomass. First p-band spaceborne SAR will be launched ∼2020; vegetation mapping and assessment. Experimental SAR.

Table 1.3. Bands with associated frequency, wavelength and typical applications. Credit: NASA

Interferometric Synthetic Aperture Radar

To disclose surface topography or motion, Interferometric[2] SAR (InSAR) techniques are applied: two or more three-dimensional observations of the same scene on Earth are compared. When the compared SAR images are taken from slightly different positions, mapping of the surface topography can be performed. On the contrary, if the combined images originated from the same position at different times, their difference shows surface motion or deformation during that time.

The resulting image is called interferogram and it is a rainbow-colored pixels fringe that represents the received signal phase difference over time, showing the change in the image.

The figure 1.12 is an example of an interferogram of the San Andreas Fault, California: the line of the fault can be clearly perceived where pink and yellow meet, in the upper half. This change in fringe color is caused by the movement of the surface that took place between the observation dates.

[2]Interferometry is an imaging technique in which waves are superimposed [6]

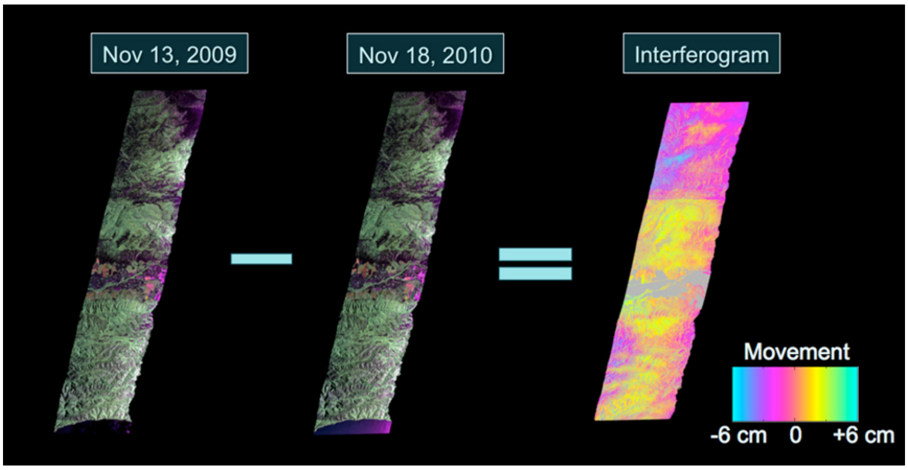

Figure 1.12. San Andreas fault interferogram example. Credit: NASA.

In contrast to what happens with SAR, which uses both the amplitude of the wave and the phase of the reflected signal, InSAR make use only of the phase difference from multiple positions or passes.
The phase is altered by the interaction with the surface, the change in perpendicular distance from satellite to ground during its orbit and the surface topography (if there are objects scattering the signals in many directions), thus it is necessary to compensate and remove to the final interferogram all the parameters affecting the phase.
Therefore the contributions of the ground surface, orbital effects and topography to the phase of the signal has to be removed and , without considering other sources of additional error, what remains in the image is the change in surface movement or deformation.

The figure 1.13 shows how InSAR measures deformation of the surface by measuring wave's phase difference between two passes, considering that a point on ground moves while the satellite remains in the same position.

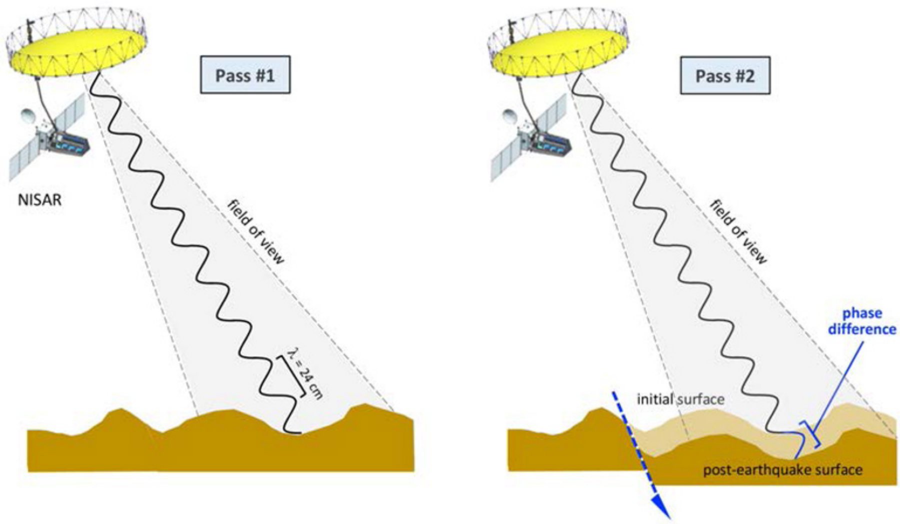

Figure 1.13. InSAR surface deformation measurements. Credit: NASA.

During the first pass, the surface of interest is imaged and the phase is measured between the satellite and the ground in the direction of Line Of Sight (LOS). Then when the second pass is completed, another measurement is performed between the satellite and the ground: in case that the ground moves between the two passes, that phase difference is proportional to the deformation of ground between the passes along the LOS direction.

1.5.8 LiDAR

LiDAR (Light Detection and Ranging or Laser Imaging Detection and Ranging) is a remote sensing method that [7] *uses light in the form of a pulsed laser to measure ranges to the Earth*. When these light pulses are combined with other airborne systems' data, it create accurate three-dimensional information about Earth shape and its surface characteristics. LiDAR is used to determine the distance of an object or surface through the use of a laser pulse and it is also able to determine the concentration of chemical species in the atmosphere and expanses of water.
A LiDAR instrument principally consists of a laser, a scanner, and a specialized GPS receiver. Airplanes and helicopters are the most commonly used platforms for acquiring lidar data over broad areas. There are two types of lidar: topographic and bathymetric. Topographic lidar typically uses a near-infrared laser to map the land, while bathymetric lidar uses water-penetrating green light to also measure seafloor and riverbed elevations.

When a targeted area is pointed at with an airborne laser, the light beam is reflected by the encountered surface, and, then, a sensor records the reflected light in order to measure a range. Note that, if laser ranges are combined with position and orientation data (from integrated GPS and Inertial Measurement Unit systems), scan angles, and calibration data, the result is a "point cloud", a dense, detail-rich group of elevation points. The main characteristics of each point in a point group are the three-dimensional spatial coordinates (latitude, longitude, and height), associated to a specific point on the surface from which the laser pulse was reflected. Moreover, the point clouds can be used to generate other geospatial products, as digital elevation models, building models, contours, etc.

To sum up, LiDAR is commonly used to create high resolution maps, with application in topology, geodesy, archaeology, geography, geology, seismology, atmospheric physics, laser guidance, laser altimetry etc. In addition, it is used for the control and navigation of some self-driving cars and was used for the Ingenuity helicopter in its data collection flights over the ground of Mars.
Over time, LiDAR systems have been adapted for UAVs, obtaining lightweight systems useful for surveillance or mapping of both natural and artificial structures with consistent improvements.

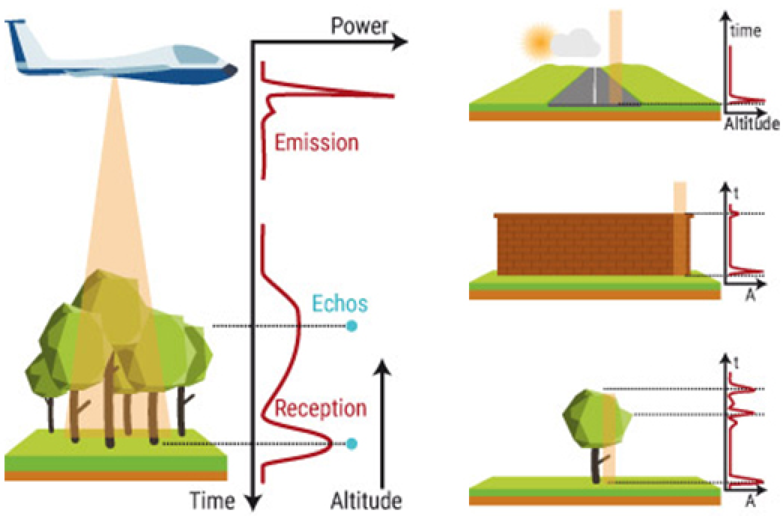

Figure 1.14. LiDAR on UAV. Credits: www.yellowscan-lidar.com

1.5.9 Doppler Sensing

The basic principle behind the use of Laser Doppler Vibrometer (LDV) is to employ measurement systems for remote acquisition and, when necessary, for remote structural excitation, instead of contact sensors. In fact, LDV is a non-contact tool that measures vibration employing the Doppler effect of light. Doppler effect is *a phenomenon in which the observed frequency of the scattered wave changes depending on the motion states of the wave (light or sound wave) source and the observer* [8], as shown in Figure 1.15.

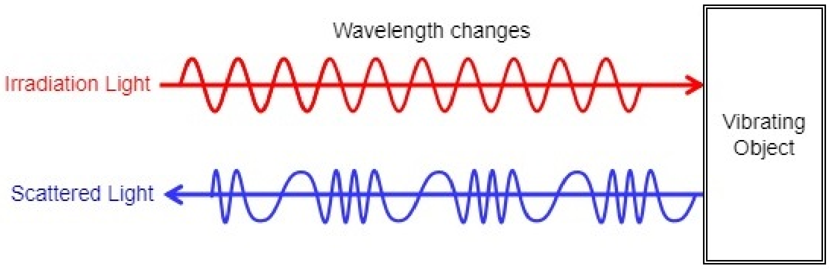

Figure 1.15. Doppler effect

The vibration can be detected by the change of wavelength of the scattered light received by the device. In fact, when light irradiated an object, scattered light is generated and, if the object is vibrating, the wavelength of the scattered light varies due to Doppler effect.
A general configuration of laser Doppler vibrometer is represented in Figure 1.16:

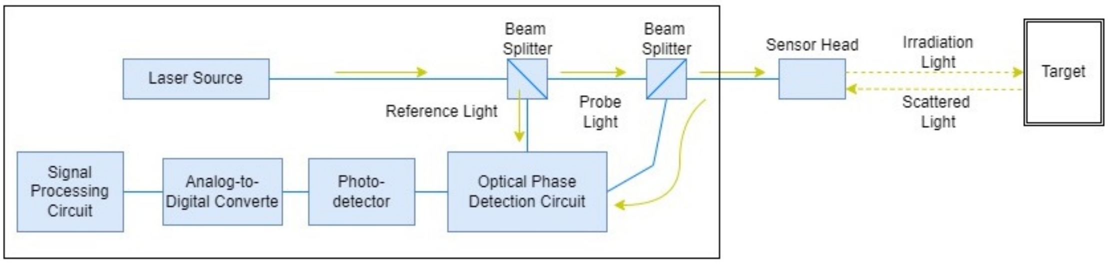

Figure 1.16. General configuration of Laser Doppler Vibrometer

LDVs are, typically, used in a wide variety applications such as scientific, industrial, and medical ones. In the Aerospace sector, these devices are used to carry out non-destructive inspection of aircraft components. Besides, LDVs could be used for structure monitoring, in civil engineering and architecture.

1.5.10 Multispectral and Hyperspectral sensors

Multispectral and hyperspectral sensors are widely employed in remote sensing applications for multiple purposes. The main feature that differentiates them from other sensors and technologies is the number of spectral bands and the range of covered wavelengths. Thus, since different materials reflect and absorb differently at different wavelengths, it is possible to differentiate materials based on their spectral reflectance signatures observed in these images, when direct identification is usually not possible.

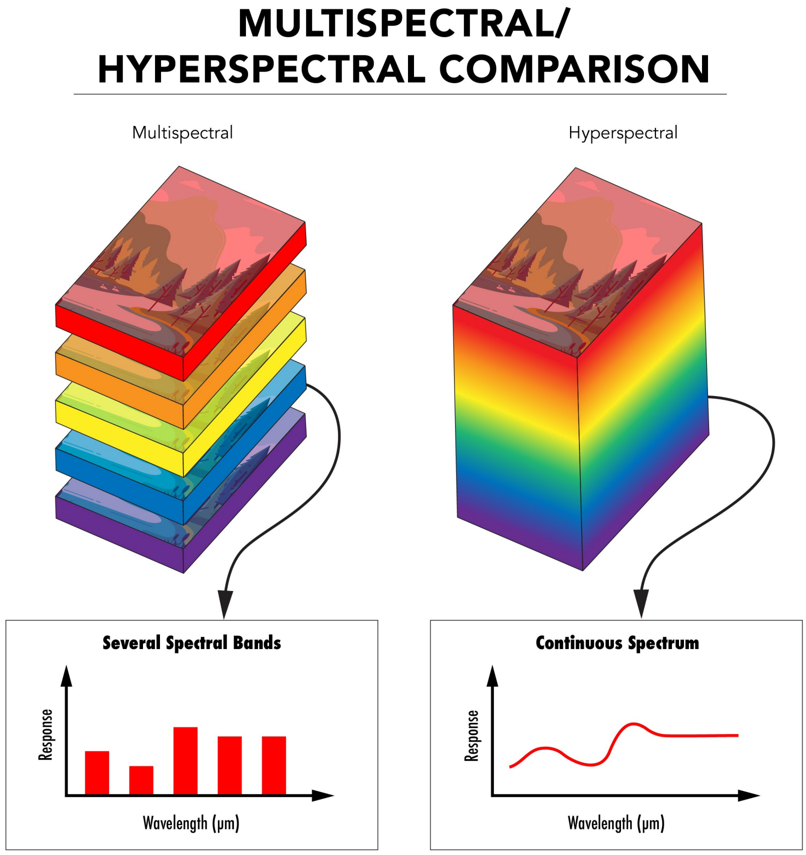

Figure 1.17. Multispectral/Hyperspectral comparison. Credits:www.edmundoptics.com

Multispectral sensors produce multispectral images by measuring the reflected energy within different bands of the electromagnetic spectrum. Multispectral sensors typically have 3 to 10 different band measurements in each pixel of the produced images. Examples of bands in these sensors include visible green, visible red, near infrared, etc.
Multispectral imaging was, originally, developed for the identification and reconnaissance of military targets. Nowadays, this technology is being used for various applications, including space imaging for Earth observation and mapping and weather forecasts (eg Landsat satellites).

Hyperspectral sensors measure energy in narrower and more numerous bands than multispectral sensors. Hyperspectral images can contain up to 200 (or more) contiguous spectral bands. The numerous narrow bands of hyperspectral sensors provide continuous spectral measurement over the entire electromagnetic spectrum and, therefore, are more sensitive to subtle variations in reflected energy. Images produced by hyperspectral sensors contain far more data than images from multispectral sensors and have greater potential for detecting differences between land and water features. Since hyperspectral sensors rely on line scanning through the movement of the platform, they require sufficient stabilization to build coherent images. Sometimes, these systems require geometric correction using specific features and ground control points.

Although hyperspectral technology was developed for mining and geology (the ability of hyperspectral imaging to identify various minerals makes it ideal for the mining and oil industries, where it can be used to search for minerals and oil), it is now widespread in fields such as ecology (information on the chemical components of materials), monitoring of the development and health of agricultural crops, surveillance, astronomy and civil engineering.

Chapter 2

The Case Study: Optimal Sensor Placement for Structural Health Monitoring

After the state of the art of remote sensing principles and technologies, the case study is presented with a brief description of Structural Health monitoring concept and an overview of Optimal Sensor Placement, in order to show the main objective of the thesis, the possibility of using remote sensing data as input for OSP. Furthermore, a series of requirements is identified and the process for choosing the OSP platform is illustrated.

2.1 Optimal Sensor Placement for Structural Health Monitoring

Structures and infrastructures are complex engineering systems that represent an important and valuable asset to society.
In fact, today's interconnected world is build upon these complex systems and, hence, the dependence of humans on these systems is of paramount importance, leading to an always increasing demand for security and reliability.
Unfortunately, structures and infrastructures are always subject to deterioration over time due to continuous use and exposure to environmental phenomena, such as variations in temperature and humidity, aging and artificially caused damage.
Therefore, this results in the need to monitor and evaluate the health conditions of the structure to avoid its failure and to be able to plan effective maintenance without destructive operations.
Traditionally, visual inspection techniques are used for their simplicity and low cost,

but these methodologies are often prone to errors and problems, mainly due to the human factor and the fact that they are only performed on a periodic basis, without considering the actual conditions.
Therefore, the necessity to obtain information on the condition of structures as continuously as possible and the increasingly strong dependence with society, highlighted the need for a Structural Health Monitoring (SHM) system.

2.1.1 SHM

SHM can be defined as [11] *the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure.*
Typically, SHM process is described as a process which involves [11] the observation of a system using dynamic response measurements periodically sampled from a sensors array, over a period of time, the extraction of damage-sensitive characteristics from these measurements, the statistical analysis of these characteristics to determine the current system's health state.
In the literature over the past decades, there are several techniques for SHM that must ideally fulfill one or more of the following requirements [11]:

- Low cost;
- Ability to perform continuous assessment;
- Sensitivity to low levels of damage;
- Sensitivity to different types of damage;
- Ability to override ambient load conditions;
- Ability to exclude noises;
- Ability to exclude changes in environmental conditions.

The most common techniques are, for example, vibration-based monitoring, elastic waves-based monitoring, comparative monitoring, strain monitoring and others. All of these techniques exploit an array of sensors that measure the periodically sampled dynamic response; subsequently, the damage-sensitive characteristics are extracted and their statistical analysis is carried out to determine the current state of health of the system.
In summary, SHM exploits sensors for the collection of data, filters for data cleasing and units for central data processing for the extraction of the characteristics, together with post processing.

2.1.2 Optimal Sensor Placement

The quality of the information collected by the sensors has an important influence on the performance of the monitoring. Consequently, over the years, the research has focused on the study of sensor technology, through the development of sensors such as fiber optical sensor, piezoelectric transducers and smart films, which however have the limit on the performance of the sensor itself.
In general, the more sensors are placed on the monitored structure, the more detailed information can be obtained to depict the structural health status.
Moreover, in real applications, monitored structure has infinite nodes but sensors can be placed only in a finite number of locations. Thus, the number of sensors is limited due to issues such as, structural inaccessibility, budget constraints, etc, and, given this limitation, sensors locations have to be optimized to obtain as much structural information as possible.
A possible improvement on this matter is implementing the optimal positioning of sensors.
In fig. 2.1, a general framework for OSP problem definition is reported, from literature [11] to give a first insight on optimal sensor placement.

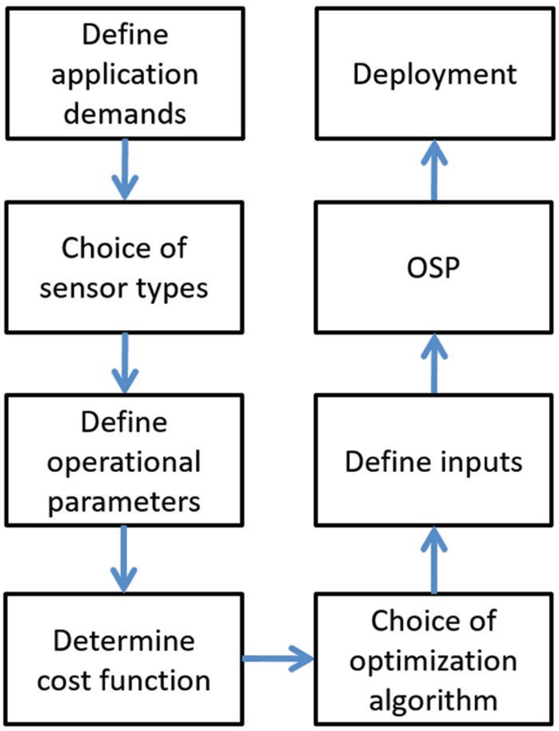

Figure 2.1. OSP Framework [11]

Firstly, the requirements of application has to be defined: they are strictly dependent on the type of SHM system. Subsequently, the sensors to be used has to be

selected and this choice is often forced by the monitoring technique, even if, nowadays, with the technological development, there is a wide range of sensors that can detect the desired quantity. Once the sensors have been chosen, the operational parameters have to be defined, including the locations of the sensors, their numbers, the limits given by the application, etc., and, then, the cost function and the optimization algorithm need to be determined.
However, the computation of the cost function and the execution of the optimization algorithm require inputs, which can be derived from numerical or analytical models but it might be obtained, in some application, from experimental data.
After the definition of inputs, optimization can be performed and optimized sensor positioning can be achieved.

2.2 Objectives & Requirements definition for Remote Optimal Sensor Placement

In this work of thesis, the main goal is to explore the possibility of using real data from remote sensing as inputs for the OSP, thus position and displacement (or speed or acceleration) in the base triad (longitude, latitude and topographic height) of a point of the actual structure, together with their variation over time. In particular, the author defines a methodology to define the way to collect these real data and, after identifying the requirements, puts this methodology into practice and identifies the most suitable platform.

Typically, OSP strategies are based on modal model estimation of a target system: firstly, a geometric model is built on the basis of drawings or specific measurements, and then a Finite Element (FE) model of the target system has to be set up, as the FE model allows the extraction of several system mode shapes by solving an eigen-analysis problem. The points that move more in the global modes of the structure the position candidates for placing the sensors. Per contra, the obtained mode shapes (i.e. the related natural frequencies) are altered by model geometric and mechanical discrepancy errors.
Consequently, System Identification, SI, has become a widespread field of research that aimed to estimate structural properties of an observed real system, starting from records of dynamic data obtained by dedicated sensors mounted on the structure [12]. SI approaches, starting from dynamic data, can be applied in order to obtain a modal model estimation of a target system, without the need of a FE model.
However, when analyzing complex structures, large in size, with difficult points to

reach, real data approach can become problematic. When, for example, the structure target is a 200 meters long bridge, an operator is needed to firstly position a number of sensors (such as 10), acquire data for period of time, then disassemble everything and re-position the sensors in other positions to acquire other data and etc. Later in the laboratory, all the data are analyzed and vibration modes are obtained from measured accelerations, to figure out where to definitively place the sensors.
This type of procedure involve numerous issues, mainly related to:

- problems of accessibility of the areas in which to install the sensors,
- difficulty in dynamic identification - difficulty in obtaining the modes of vibrations from the measured accelerations (this instead is immediate to do on a numerical model),
- direction of acquisition - in fact it is not enough to define a sensor position, it is also necessary to investigate the optimal direction.

Therefore, it is necessary to define the best methodology to remotely collect data, avoiding all the aforementioned problems, and use the data collected subsequently for OSP, avoiding the employment of the model and its related uncertainties.

2.2.1 Requirements identification

For this purpose, a series of requirements have been identified: the table 2.1 shows the main specifications that a remote equipment shall meet to successfully perform remote OSP functions.

IDENTIFIER	TEXT	COMPONENTS	TAGS
OSP_010	Uncertainty in georeferencing shall be as less as possible (i.e. less than 0.5/1 m)	*Platform/Payload*	Georeferencing
OSP_020	Uncertainty in synchronization shall be less than one thousandth of the time resolution (OSP_060) (i.e., less than 1e-4/1e-6 seconds)	*Platform/Payload*	Synchronization
OSP_030	Spatial covering shall be as much as possible, and shall have at least one point with 3 directions common in deferred acquisitions	*Platform/Payload*	Spatial covering
OSP_040	Acquisitions time shall be as less as possible (i.e., 4 hours), otherwise repeat the acquisitions in a different period at the same time	*Platform*	Acquisitions time
OSP_050	Spatial resolution shall be as less as possible (i.e., less than 2 meters) and shall be higher than 2 times the uncertainty in georeferencing (OSP_010)	*Platform/Payload*	Spatial resolution
OSP_060	The time between 2 observation of data shall be between 0.002 and 0.01 seconds (sample frequency between 100 and 500 Hertz)	*Payload*	Time resolution
OSP_070	Frequency resolution shall be less than 0.0033 Hertz (signal duration higher than 5 minutes)	*Payload*	Frequency resolution
OSP_080	Data sensitivity shall be higher than 1 Volt/gravity (for accelerations)	*Platform/Payload*	Data sensitivity

Table 2.1. Requirements for remote OSP tasks

The types of requirements (tags) [12] are listed as follows:

- Georeferencing: The target monitored structure needs to be located in a stable spatial reference system, so that the position of the monitored points in time remains adequately constant.

- Synchronization: During the acquisitions the different records must refer to a stable time reference system, so that the time frames acquired for different points remain aligned.

- Spatial covering: The acquisitions should cover as much as possible the entire spatial dimension of the target structure. If this is not possible, asynchronous acquisitions can be contemplated (acquisitions deferred over time). In this case, for the different deferred acquisitions, at least one point and three directions must be stables out of the period of the synchronous records. This is required to link together the modal models estimated in deferred times, obtaining the unique (enriched) modal model of the structure.

- Acquisitions time-gap: Clearly, in case of deferred acquisitions, the time-gap between two different acquisitions must be as less as possible to avoid physiological changes of the target system due to the presence of Environmental and Operational Variations (EOVs), which cannot be eliminated.

- Spatial resolution: To get a good spatial approximation of the modal model of the target structure, the acquired displacements, velocities, or accelerations must be referred to adequately close monitored points.

- Time resolution (or Sample frequency): the time resolution, or sample time (i.e., the inverse of the sample frequency), needs to be adequately high to capture the main vibrations modes of the target structure, but relatively low so as not to reduce the SNR of the signal too much.

- Frequency resolution (or Signal duration): the frequency resolution (i.e., the inverse of the signal duration), must be as low as possible in order to increase the frequency localization of fundamental modes of the structure.

- Data sensitivity: The equipment, as well as the payload of the remote technology must ensure an adequate level of sensitivity, so that the data acquired between two time frames at the same point (during a synchronous acquisition) can differ due to the presence of instantaneous and constantly changes in the EOVs.

2.3 Decision analysis process

Once the research of the state of the art of platforms and sensors for remote sensing has been completed and the requirements have been identified, it is necessary to identify a methodology for selecting any solutions on the basis of criteria that should be as objective, clear and independent as possible.
To this purpose, NASA states that decision analysis offers a methodology for making decisions and, in particular, it can be used to help evaluate problems, alternatives and their uncertainties to support decision making [13].
One effective decision support tool is the Analytical Hierarchy Process (AHP), which is a Multi-Criteria Decision Analysis (MCDA) method: it can be used to select the optimal option between a number of choices and prioritize requirements and/or criteria. It employs a multi-level hierarchical structure composed of criteria, sub-criteria, objectives, and alternatives [14]. Subsequently, the data are extracted by adopting a set of pairwise comparisons: the main results of these comparisons is the obtaining of decision criteria weights of importance, and, accordingly, the performance measures of the alternatives.
AHP Process, as stated in the NASA Systems Engineering Handbook, follows six steps:

1. Describe in summary form the alternatives under consideration

2. Generate high-level Figures of Merit (FoM)

3. Decompose high-level FoMs into a hierarchy of evaluation attributes

4. Determine relative importance of FoMs through prioritization matrix and pairwise comparisons

5. Make pairwise comparisons of the alternatives with respect to each of the FoMs

6. Iterate until consensus is reached

As follows, figure 2.3 shows an example of AHP computational procedure to discover the final weight of each criterion/attribute,

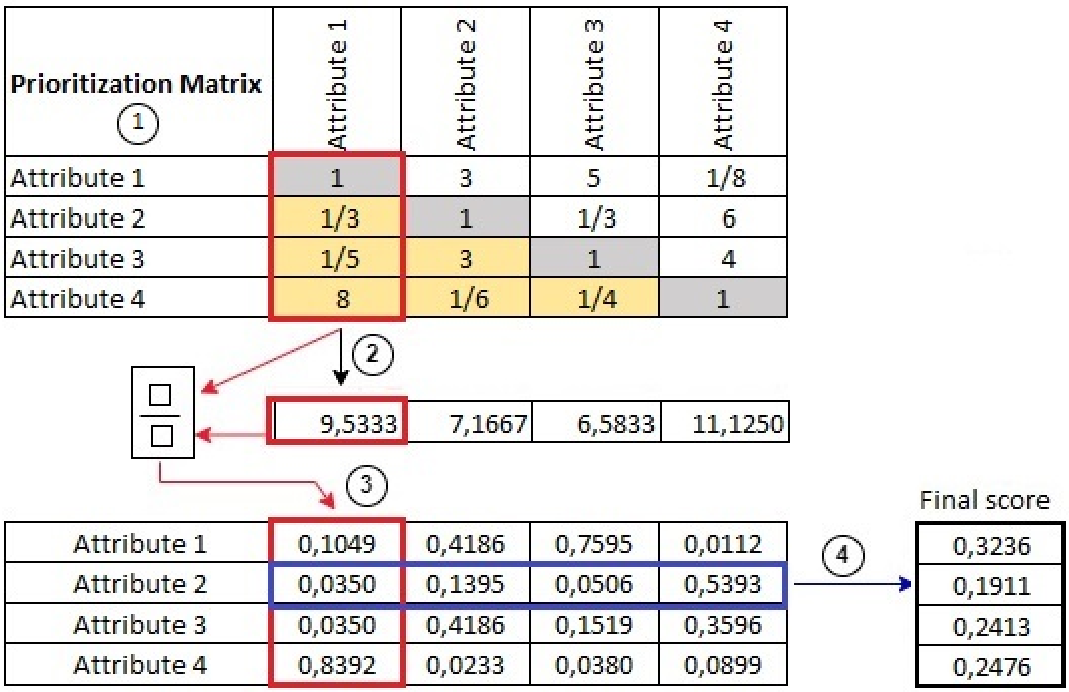

Figure 2.2. AHP Computational Procedure: criteria score

where four steps are followed:

1. Define relative preferences on a scale, for example from 1 to 9 - 1 is neutral, 3 Moderately Prefer, 5 Strongly Prefer, 7 Very Strongly Prefer and 9 Extremely Prefer;

2. Sum each column;

3. Normalize each column by its sum;

4. Average each row to find the final score for each criterion.

Afterwards, we compare each solution with the criteria identified above, assigning a value, for example from 1 to 9, where 1 is not at all satisfying the criterion and 9 completely satisfying it.

	Final score
Attribute 1	0,3236
Attribute 2	0,1911
Attribute 3	0,2413
Attribute 4	0,2476

	Attribute 1	Attribute 2	Attribute 3	Attribute 4	Final score	Ranking
Solution A	2	5	1	8	3,8245007	3
Solution B	7	7	3	2	4,8216078	2
Solution C	4	8	3	1	3,7944807	4
Solution D	6	7	6	8	6,7072332	**1**

Figure 2.3. AHP Computational Procedure: solution choice

The final result is obtained by multiplying the value assigned to each attribute for each solution by its weight and then adding them together. In the end, the best solution is identified as the first in the ranking.

Chapter 3

Remote Sensing Platforms evaluation and determination

At this point, the most suitable remote sensing platform can be chosen, using the methodology previously explained, after illustrating the types of these platforms in detail.

3.1 Types of Remote Sensing Platforms

For remote sensing application, sensors have to be mounted on suitable stable platform, which, in general, is a stage where sensor or camera or other device is mounted to gain information about a specific target. There are different kind of platforms, mainly based on its altitude above earth surface: higher the sensor is mounted, larger the spatial resolution is and the observational area is increased. These platforms can be located on the ground, on platforms within Earth's atmosphere or on a spacecraft or satellite outside the atmosphere.
The choice of most suitable platform, to study a given phenomenon, depends on the resolution of data that allows to describe the changes associated with that process, thus making possible to identify, measure and forecast changes. The selection is, therefore, strictly dependent on the spatial scale and purpose of the study.

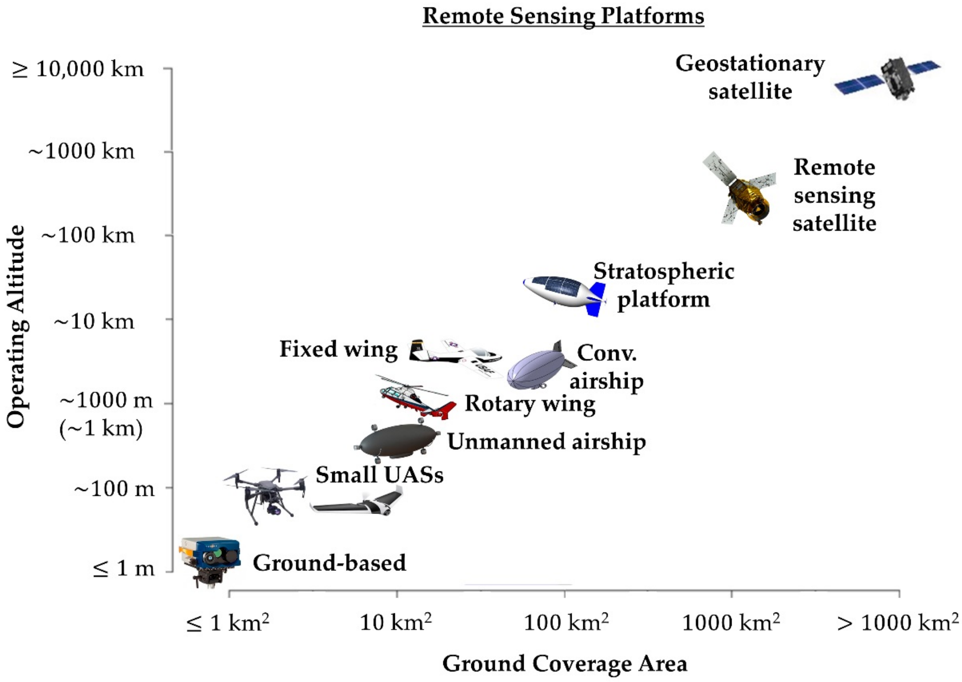

Figure 3.1. Remote Sensing Platforms [15]

3.1.1 Ground-borne Platforms

Ground platforms are typically used to acquire information on the surface, to be compared with that from aircraft or satellite sensors, for example for ground observation. Furthermore, these platforms are also used for sensor calibration, quality control and for the development of new sensors.
Ground platforms commonly include handheld devices, tripods, towers, cranes, portable masts and vehicles etc; they provide up to 50 meters elevated data and they are useful for acquiring low altitude imagery with frequent coverage for dynamic phenomena.
These platforms are low cost, relatively stable (apart from the masts that have stability problems in windy conditions) and provide high-resolution data

3.1.2 Air-borne Platforms

Air-borne platforms involve balloons, unmanned aerial systems (UAS), airplanes, high altitude aircraft and helicopters. These platforms are employed to collect detailed images and they can provide up to 50 km elevated data, useful for the acquisition of atmospheric data. Moreover, air-borne platform can be applied for specific tasks as building maintenance, mapping, environmental monitoring and precision agriculture.

Balloons

Balloons are air-borne platforms for remote sensing observation applications, such as aerial photography, and for nature conservation studies. These float, generally, at a constant height of around 30km, which, being a higher altitude than aircraft, gives larger synoptic views.
Balloons are composed of a rigid circular base that supports the sensor system, protected by an insulating and shock-resistant but lightweight casing.
These devices are not very expensive compared to airplanes and can be built in various shapes and sizes, with even different capacities. Furthermore, they do not require power and have low accelerations and low vibrations.
However, they are not widely used, because they are not very stable and they are subject to meteorological unpredictability, even if small balloons can still be used for meteorological research.

Unmanned Air System

UAS[1] is an aerial vehicle without an onboard pilot that can be remotely controlled or can operate autonomously.
UAS is designed to satisfy the need for low cost platforms with long endurance and ability to operate without or with just a small runway, but with a modest payload capacity.
Drones preset different purposes in order to collect remotely sensed data, such as research, agriculture, photography, infrared detection, radar observation and others.
The most interesting and unique advantage is that UAS can be precisely positioned above the area to be monitored and capable of acquiring both day and night data.

Aircraft

Aerial platforms are mainly stable wing aircraft, although helicopters are occasionally used: aircraft are used to acquire very detailed images, while helicopters can be applied for pinpoint locations but present problems related to vibrations and lack of stability.
Generally, aircraft with cameras and sensors mounted on vibration-less platforms can be used to acquire aerial photographs and images of surface features.
On the basis of flight altitude, different types of information are collected: by acquiring aerial photographs at low altitude, large scale images are obtained providing

[1] Unmanned aerial vehicle (UAV), unmanned aircraft systems/vehicles, remotely piloted aircraft (RPA) and drone, are used interchangeably.

detailed information, while, by acquiring data at high altitude, smaller scale images are obtained, which have the advantage of covering a larger area with low spatial resolution.
In addition to aerial photography, aircraft can carry out multi spectral, hyperspectral and microwave imaging.

If on one hand an aircraft has the advantage of being in the right place at the right time, on the other we can observe that there is a problem with the stability of the platform. In fact, an airplane flying in the atmosphere is subject to two types of instability: the vibrations generated by the engines or other parts and the rotations due to the dynamics of the airplane and the atmosphere.
However, instability can be reduced in two main ways. One possibility is to isolate the sensor from vibration through a mount and to maintain the attitudes of the sensor regardless of the rotation of the aircraft, using devices such as gyroscopes.
The other way is to design and/or select aircraft and equipment; for example, if you choose a turbine engine or, better, a jet, vibrations are reduced.

Low-altitude aircraft are used extensively and operate below 9 km (30,000 ft), with single/twin engine. These aircraft are used to collect image data in small areas with large scale.
High-altitude aircraft, on the other hand, operate above 9 km and are more stable. These aircraft obtain data for large areas, with smaller scale.

The aircraft platform captures image data in suitable atmospheric conditions. It checks and controls platform variables as altitude and time of coverage. However, aircraft are expensive and present motion blurring; they are, also, less stable than space-borne platforms.

Rocket as a platform

Sounding rockets at high altitude can be useful platforms for testing the reliability of remote sensing techniques and their dependence on the distance to the target. These rockets can be used at moderate altitudes, as an intermediate platform between balloons and satellites, collecting image data with moderate synoptic view.
A mobile launcher fires the high altitude sounding rocket and, subsequently, the scanning work is performed during the flight from a stable altitude. Then, it returns to the ground by parachute, allowing the recovery of the data.
The main limitation of this platform is the difficulty of the descent phase and its unpredictability which could cause damage.

3.1.3 Space-borne Platforms

Space-borne platforms involve sensors mounted onboard spacecraft, orbiting around the Earth, and they may have a high initial cost but a relatively low cost per unit of coverage area. They can acquire data of the entire earth and their imaging ranges up to altitude of 36,000 km (geostationary orbits).
Hence, platforms are no longer as limited by the atmosphere as for air-borne platforms and their orbits can be designed so that:

- any desired altitude is maintained as long as the spacecraft is above the effects of aerodynamic drag but still under the effect of the earth's gravitational field;
- the portion to be observed is covered at specific intervals thanks to the chosen configuration;
- if you have geostationary spacecraft, the position relative to the surface is maintained, allowing continuous sensing.

In this way, performing remote sensing of the whole earth on a periodic basis and remote sensing of a portion on a continuous basis is feasible.
Satellites used for remote sensing are usually designed as unmanned, although manned space stations can provide similar sensing.

3.2 Remote sensing platforms comparison

As already previously stated, the generic goal of remote sensing technologies is to observe some physical parameters in a mapping frame, during a given time period, or given time [17].
An effective way to illustrate the observation interval is presented by Toth et al. and it is shown in the figure 3.2 as a cube, defined by three sensors parameters:

1. the Ground Sampling Distance (GSD) - spatial resolution;
2. the review time, or frequency of data acquisition;
3. the object range - average distance between the sensor and the target.

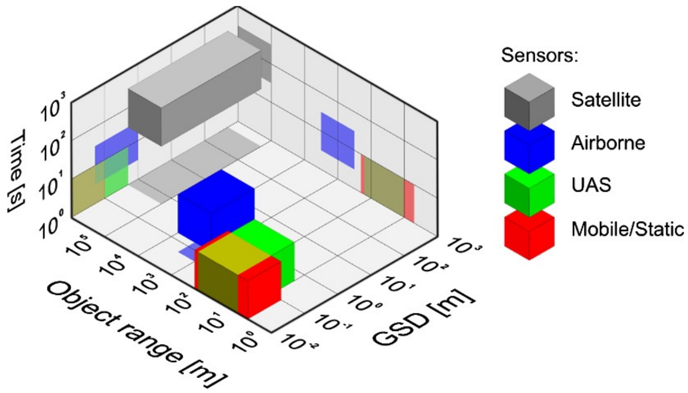

Figure 3.2. Observation cube

In this case, note that the definition of the spectral aspect is not included for simplification. In fact, there are undoubtedly several aspects that characterize remote sensing platforms, and sensors, however this figure is intended to represent a generic orientation with respect to principal parameters.

For completeness of analysis, the table 3.1 lists the most frequently used parameters to characterize remote sensing systems.

	Platforms			
Attributes	**Space-borne (satellite)**	**Air-borne (aircraft)**	**UAS**	**Ground-borne**
Maneuvrability	None/limited	Moderate	High	Limited
Sensors diversity	MS/HSI/SAR	MS/HSI/LIDAR/SAR	MS (LIDAR/HSI)	MS/LIDAR(HSI)
Ground coverage	Large (10 km)	Medium (1 km)	Small (100 m)	Small (50 m)
Scale	Small	Small/medium	Medium/large	Medium/large
Repeat rate	Days	Hours	Minutes/hours	Minutes
Spatial resolution (GSD)	0.30-300 m	5-25 cm	1-5 cm	1-5 cm
Stability	High	Moderate	Moderate	High
Deployability	Difficult	Complex	Easy	Moderate
Observability	Vertical/oblique	Vertical/oblique	Vertical/oblique/360°	Oblique/360°
Operational risk	Moderate	High	Low	Moderate
System cost	€€€€	€€€	€	€€

Table 3.1. Typical platform configurations wrt main operational attributes

As shown in table 3.1, if on one hand the main sensors, as active/passive imagers, are typically available on all platforms, on the other hand the object range is strongly related to complexity and performance of the system and to its price. Moreover, it can be stated that optical sensors can produce almost identical spatial resolution across all platforms. However, ground coverage, repeat rate, spatial resolution, among the others, significantly vary by platforms.

3.3 Decision Making: platform selection

At this point, the decision making process is carried out in order to select the most suitable platform for the OSP application, through the methodology explained in the section 2.3.

The work was set up as follows.

First of all, 11 attributes or figures of merit were identified, that correspond to those indicated in table 3.1.
The prioritization matrix was, then, completed considering a scale between 0 and 5, dispensing the blank matrix to five members of the research team in order to have more balanced weights of the attributes, considering different opinions and visions. As an example, one of the prioritization matrices is shown in figure 3.3: in this case, there are in the first three positions repeat rate, spatial resolution and stability, in the classification of importance of the attributes.
Subsequently, the results of the weights provided by the different team members were combined, obtaining the weights and the final classification of the attributes needed to evaluate the choice of the platform.
Overall, it can be seen in figure 3.4 that the first two attributes by importance (spatial resolution and repeat rate) are the same as in the matrix taken as an example, while in the third place there is observability instead of stability, currently in seventh place.

PRIORITIZATION MATRIX

	Maneuvrability	*Sensors diversity*	*Ground coverage*	*Scale*	*Repeat rate*	*Spatial resolution (GSD)*	*Stability*	*Deployability*	*Observability*	*Operational risk*	*System cost*	**Weight**	**Ranking**
Maneuvrability	1.00	0.5	0.33	0.33	0.20	0.20	0.25	0.33	0.33	0.50	0.33		
Sensors diversity	2.00	1.00	0.33	0.33	0.20	0.20	0.20	0.25	0.25	0.50	0.33		
Ground coverage	3.00	3.00	1.00	0.50	0.25	0.25	0.33	0.33	1.00	3.00	4.00		
Scale	3.00	3.00	2.00	1.00	0.50	0.50	2.00	3.00	1.00	0.50	1.00		
Repeat rate	5.00	5.00	4.00	2.00	1.00	1.00	3.00	3.00	4.00	2.00	4.00		
Spatial resolution (GSD)	5.00	5.00	4.00	2.00	1.00	1.00	3.00	3.00	3.00	3.00	4.00		
Stability	4.00	5.00	3.00	0.50	0.33	0.33	1.00	2.00	0.50	2.00	3.00		
Deployability	3.00	4.00	3.00	0.33	0.33	0.33	0.50	1.00	0.33	2.00	2.00		
Observability	3.00	4.00	1.00	1.00	0.25	0.33	2.00	3.00	1.00	0.33	0.50		
Operational risk	2.00	2.00	0.33	2.00	0.50	0.33	0.50	0.50	3.00	1.00	0.50		
System cost	3.00	3.00	0.25	1.00	0.25	0.25	0.33	0.50	2.00	2.00	1.00		
	34.00	35.50	19.25	11.00	4.82	4.73	13.12	16.92	16.42	16.83	20.67		
Maneuvrability	0.03	0.01	0.02	0.03	0.04	0.04	0.02	0.02	0.02	0.03	0.02	0.0254	11.00
Sensors diversity	0.06	0.03	0.02	0.03	0.04	0.04	0.02	0.01	0.02	0.03	0.02	0.0281	10.00
Ground coverage	0.09	0.08	0.05	0.05	0.05	0.05	0.03	0.02	0.06	0.18	0.19	0.0775	7.00
Scale	0.09	0.08	0.10	0.09	0.10	0.11	0.15	0.18	0.06	0.03	0.05	0.0951	4.00
Repeat rate	0.15	0.14	0.21	0.18	0.21	0.21	0.23	0.18	0.24	0.12	0.19	0.1871	1.00
Spatial resolution (GSD)	0.15	0.14	0.21	0.18	0.21	0.21	0.23	0.18	0.18	0.18	0.19	0.1870	2.00
Stability	0.12	0.14	0.16	0.05	0.07	0.07	0.08	0.12	0.03	0.12	0.15	0.0989	3.00
Deployability	0.09	0.11	0.16	0.03	0.07	0.07	0.04	0.06	0.02	0.12	0.10	0.0782	6.00
Observability	0.09	0.11	0.05	0.09	0.05	0.07	0.15	0.18	0.06	0.02	0.02	0.0819	5.00
Operational risk	0.06	0.06	0.02	0.18	0.10	0.07	0.04	0.03	0.18	0.06	0.02	0.0748	8.00
System cost	0.09	0.08	0.01	0.09	0.05	0.05	0.03	0.03	0.12	0.12	0.05	0.0659	9.00

Figure 3.3. An example of prioritization matrix

FINAL ATTRIBUTES' WEIGHTS	#1	#2	#3	#4	#5
Maneuvrability	0.0390	0.0292	0.0254	0.0708	0.1645
Sensors diversity	0.0363	0.0394	0.0281	0.1050	0.0464
Ground coverage	0.0844	0.0583	0.0775	0.1666	0.0681
Scale	0.0207	0.0213	0.0951	0.0511	0.0751
Repeat rate	0.1439	0.2314	0.1871	0.1125	0.1155
Spatial resolution (GSD)	0.2867	0.1896	0.1870	0.1412	0.1441
Stability	0.0452	0.1295	0.0989	0.0267	0.0745
Deployability	0.0523	0.0457	0.0782	0.0317	0.0557
Observability	0.1134	0.1054	0.0819	0.0643	0.1208
Operational risk	0.0978	0.0722	0.0748	0.0528	0.0777
System cost	0.0802	0.0781	0.0659	0.1772	0.0575

	Weight	Final Ranking
Maneuvrability	0.0658	8
Sensors diversity	0.0510	11
Ground coverage	0.0910	5
Scale	0.0527	10
Repeat rate	0.1581	2
Spatial resolution	0.1897	1
Stability	0.0750	7
Deployability	0.0527	9
Observability	0.0972	3
Operational risk	0.0751	6
System cost	0.0918	4

Figure 3.4. Final attributes' weights

Afterwards, table 3.5 is filled comparing each solution (platform) with the criteria identified, assigning values 0-5, and the final result is obtained by multiplying the attribute's value by each solution by its weight and then adding them together.
In the end, after the decision making process, it is obtained that the choice of the optimal platform falls on the UAV/UAS.

PLATFORM FINAL CHOICE

Platform	0.0658 *Maneuvrability*	0.0510 *Sensors diversity*	0.0910 *Ground coverage*	0.0527 *Scale*	0.1581 *Repeat rate*	0.1897 *Spatial resolution (GSD)*	0.0750 *Stability*	0.0527 *Deployability*	0.0972 *Observability*	0.0751 *Operational risk*	0.0918 *System cost*
Space-borne (satellite)	1	3	5	2	1	2	5	2	3	2	2
Air-borne (aircraft)	3	4	3	3	2	3	3	1	3	1	2
UAV/UAS	4	2	2	4	4	5	3	5	5	5	5
Ground-borne	2	2	2	4	4	5	4	3	3	3	4

	Score	Ranking
Space-borne (satellite)	2.422248216	4
Air-borne (aircraft)	2.545609994	3
UAV/UAS	4.147424907	1
Ground-borne	3.549146212	2

Figure 3.5. Platform final choice

Chapter 4

UAV Remote Sensing

Finally, the selection process being completed, a general overview of drones is presented, including their classification and main characteristics, the main advantages and disadvantages and the on-board sensors and technologies that can be mounted on-board. To conclude, possible configurations, that can potentially be used for OSP purposes, are reported from literature.

4.1 General overview of drones

Unmanned Aircraft Systems (UAS), also referred to as drones, unmanned aerial vehicles (UAVs), and remotely piloted aircraft (RPA) are flying vehicles, which operate though a remote or autonomous control, without the physical presence of a pilot on board.
Recent advancements in production processes, navigation, remote control capabilities and energy storage systems allowed the development of a wide spectrum of drones, with various shapes and sizes, which can be used for different purposes and in different situations and areas, where human presence can be difficult, dangerous or even impossible. In fact, the size and type of equipment installed on board vary depending on the mission of the drone.

4.1.1 Classification of drones

There are different classifications for drones based on different parameters.

Watts et al. [18] illustrate a variety of platforms, identifying advantages of each with respect to the demand of users in scientific research. In fact, they classify the platforms for civil scientific and military uses based on characteristics, as size, flight endurance, capabilities etc. They use the following class nomenclature in the civilian realm:

- MAV (Micro (or Miniature) or NAV (Nano) Air Vehicles): their size, typically, enables military versions to be transported within backpacks of soldiers. They operate at very low altitudes (less than 330 m), with limitations on battery capacity, due to their size, leading to short flight times of ca. 5–30 min.
- VTOL (Vertical Take-Off Landing): they do not require a takeoff/landing run, and, therefore, they are chosen in situations of terrain limitations. They operate at different altitudes depending on mission profile, but typically at low altitudes. Their flight duration is limited by high requirements of power, except for larger sizes of VTLOs.
- LASE (Low Altitude, Short-Endurance): also known as small unmanned aircraft systems, they also do not need runways. They usually weighs ca. 2–5 kg, with wingspans less than 3 m to; therefore they can be launched from miniature catapult systems, or by hand. However, these compromises between weight and capability reduce endurance to 1–2 h and communication ranges within a few km to ground stations.
- LASE Close: they do require runways, but they have larger size and weight conferring increased capabilities. These systems operate at altitudes up to ca. 1500 m and may remain aloft for multiple hours.
- LALE (Low Altitude, Long Endurance): they may carry payloads of several kg at altitudes of a few thousand meters for extended periods.
- MALE (Medium Altitude, Long Endurance): they are typically much larger than low-altitude classes, and operate at altitudes up to ca. 9000 m and can fly hundreds of km from their ground stations, lasting many hours.
- HALE (High Altitude, Long Endurance): the largest and most complex, they may fly at altitudes of 20000 m or more traveling thousands of km.

Arjomandi et al.[19] classified drones on the basis of weight, range and endurance, wing loading, maximum altitude, and engine type. For instance, they classified drones as super-heavy (more than 2000 kg), heavy (200 kg - 2000 kg), medium (50 kg - 200 kg), light/mini (5 kg - 50 kg), and micro drones (less than 5 kg) [19]. This classification based on weight is shown in Table 4.1 .

Class	Weight range
Super heavy	W>2000 kg
Heavy	200 kg <W<2000 kg
Medium	50 kg <W<200 kg
Light	5 kg <W<50 kg
Micro	W<5 kg

Table 4.1. Categorization bu Arjomandi et al. based on drones' weight

The author decided to subdivide the UAVs into four categories, for the type of application of the study case and in order to simplify the final choice: (i) multi-rotor drone; (ii) fixed-wing drone; (iii) single-rotor drone; (i) hybrid fixed-wing Vertical Take-Off and Landing (VTOL) drone.

I. **Multi-rotor drone**

Multi-rotor drones are aircraft with more than two lift-generating rotors; they are one of least complex and cheapest options and offer good control over position and framing. In fact, there is a simpler rotor mechanics for flight control and fixed pitch blades are often used: to control the movement of the aircraft, one acts by varying the relative speed of each rotor to modify the thrust and produced torque.

There can be different configurations depending on the number of rotors, among which there are configurations with 3 rotors (tricopters), 4 rotors (quadcopters), 6 rotors (hexacopters) and 8 rotors (octocopters). Today, the four-rotors configuration is the most common and widespread among multi-rotor drones.

Figure 4.1. An example of multirotor drone. Credits: www.dronionline.net

Main applications

- Visual inspection
- Thermal reports
- Aerial photography and video
- 3D scans

Advantages

- Better control of the aircraft during flight.
- Thanks to the greater maneuverability, the drone can move up and down on the same vertical line, back and forth, sideways and rotate around its own axis.
- Ability to fly and hover very close to the structures.
- Due to its characteristics, the multi-rotor drone can support multiple payloads for a single flight, increasing its operational efficiency and reducing the time spent on inspections.

Disadvantages

- Multi-rotor drones have both limited life and speed, making them unsuitable for large-scale aerial mapping, long-range monitoring and long-distance inspection, such as ones for pipelines, roads and power lines.
- Due to the need for rapid and high-precision throttle changes to keep these drones stabilized, it is not possible to use a motor other than the electric one to power the multi-rotors.

- They are rather inefficient and require a lot of energy to be able to fight the force of gravity and move in the air.
- With current battery technology, if a payload, such as a lightweight camera, is mounted on the multi-rotor, the flight is limited to a duration of approximately 20-30 minutes. If more weight need to be carried (heavy-lift multi-rotor drones are used), there are much shorter flight times.

II. **Fixed-wing drone**
Fixed-wing drones have a rigid wing, similar in appearance and operation to that of airplanes. In fact, a fixed-wing drone has a rigid structure that generates lift under the wing due to the speed gained by advancing forward. Consequently, fixed-wing UAVs require much less energy in cruise mode while they acquire data, thanks to passive lifting, and have longer time and travel ranges, together with better energy efficiency. However, they require manual or runway take-off, and vertical take-off and landing will not be possible and will not be able to be stationed in the air.

Figure 4.2. An example of fixed-wing drone. Credits: www.uavgl.com

Main applications

- Aerial mapping
- Surveying - environmental, coastal, pipelines, etc.
- Support and control for agriculture, construction, security
- Inspection

Advantages

- Fixed wing drones cover greater distances and, therefore, can map larger areas. Average flight times are around a couple of hours, but with higher fuel energy densities (gas engine), the flight can be extended to more than 16 hours.
- It is possible to fly at higher altitudes and carry heavier payloads than other types of drones

Disadvantages

- Fixed wing drones are expensive and require training to be able to launch, maneuver, control them.
- They cannot be stationed over a specific point and need more space to operate.
- An extended take-off/landing area is required.

III. **Single-rotor drone**

Single-rotor drones are a robust and durable type of aircraft. They are similar to a helicopter in both structure and design: they employ a single rotor, which acts as a small airfoil that spins at high speeds to capture the flow of air and its flow is pushed down causing a difference in pressure that creates a suction effect, generating lift. To control and vary the direction in which they travel, the angle of the helix is altered.

Figure 4.3. An example of single-rotor drone. Credits: www.prodrone.com

Main applications

- Surveying

- Monitoring
- ISTAR (Intelligence, Surveillance, Target Acquisition, and Reconnaissance)
- Aerial photography and video
- Transport of heavy payload

Advantages

- Main rotor can rotate slower saving energy, but generating the same amount of lift as a multi-rotor
- They can remain stationary for long periods of time, carrying even heavier payloads (e.g. LiDAR laser scanner), and, at the same time, perform a fast forward flight.
- They can operate for longer periods of time than other types of rotary wing UAVs.
- Take-off and landing in small spaces (without runway).

Disadvantages

- Expensive and complex.
- The presence of multiple moving parts causes the onset of vibrations that make the platform less stable and the complexity of the aircraft itself requires extensive maintenance.
- Compared to multi-rotor, this type of drone is slower and, in the event of a transverse gust of wind, the effectiveness of the rotor is reduced.
- They typically have smaller payload capacities than other types of drones and are noisier.

IV. **Hybrid Fixed-wing VTOL drone**
The hybrid fixed-wing UAV is a type of drone that combines the advantages of the fixed wing of the fixed-wing drone, with the multiple rotors common to multi-rotor drones. Typically, these drones have rotors attached to their wings and this configuration allows them to both hover and take off/land vertically. Hybrids are designed to maximize efficiency, speed and range.

Figure 4.4. An example of hybrid drone. Credits: www.technosysind.com

Main applications

- Commercial applications, such as agriculture, research studies, etc.
- Collection of security information or surveillance footage.

Advantages

- Combines the stability and strength of a fixed-wing model, while taking advantage of the ease of take-off and landing of the multi-rotor.
- They can be used for both hovering and forward flight.

Disadvantages

- More expensive than simple multi-rotor and less common on the market.
- The technology behind this type of aircraft is still under development.
- Training is required to use it.

4.1.2 Miniaturization - small UAV

These are small drones, which, however, are able to provide valuable information thanks to micro cameras mounted on board.
The miniaturization of sensors and systems, although still under development, allow the improvement of the performance and reliability of unmanned aircraft and reduce their costs as well as their size. A wide range of these small drones are currently available and their size allows complex maneuvers and easier navigation in different specific environments. However, the major limitation is the correct application of a detection algorithm that allows them to avoid obstacles and achieve full autonomy.

Figure 4.5. Different types of µUAVs, (a) HTOL, (b) VTOL, (c) tilt-rotor, (d) tilt-wing, (e) tilt-body, (f) ducted fan µUAV, (g) helicopter, (h) ornithopter, (i) ornicopter, (j) cyclocopter, and (k) unconventional µUAV [20]

Small UAVs are commonly classified based on their weight and normal operating altitude, as shown in table 4.2.

Type	Mass	Operative altitude	Mean mission range	Examples
Micro	<2 kg	>50 m	5 km	AR Drone, DraganFlyer X6, The eBee senseFly, DJI Phantom
Mini	2-20 kg	>1 km	25 km	AeroVironment Puma of NOAA, DJI Inspire
Small	>20 kg <150 kg	>1.5 km	50 km	Integrator System of INSTIU

Table 4.2. Classification of small drones

Micro-UAVs have a wingspan of just a few centimeters and tend to operate at very low altitudes (< 1 km). Generally the degree of autonomy is between 5 and 30 min. Mini-UAVs have a size of several tens of centimeters and a typical effective flight time of around 40 min.

Small UAVs have greater weights and dimensions (of the order of one to three meters). They may require take-off and landing runways depending on their configuration. They operate at up to 1500m of altitude and represent a long-lasting standalone solution of several hours.

4.1.3 Main advantages and disadvantages of this technology

A summary table is reported below to show the main advantages and disadvantages of using the four main categories of drones, previously studied.

Type	Advantages	Disadvantages
Multi-rotor	- Accessibility - Ease of use - VTOL and hovering - Good control (e.g. for video / cameras)	- Limited autonomy - Limited payload capacity
Fixed-wing	- High autonomy - Extended coverage area - High flight speed	- Takeoff and recovery take a lot of space - No VTOL and hovering - More complicated to maneuver and requires flight training - Expensive
Single-rotor	- VTOL and hovering - High autonomy (with gas power) - Capacity for heavier payloads	- Dangerous - Difficult to maneuver and training required - Expensive
Hybrid	- VTOL - High autonomy	- Not perfect for either hovering or classic flying - Still under development

Table 4.3. Advantages and Disadvantages of the main UAV configurations

Looking at Table 4.3, it can be concluded that there is no unique preferred or optimal solution a priori, but it is necessary to identify the type of payloads for the application of interest, their requirements and the resources available in order to choose the most suitable type.

4.1.4 On-board sensors and technologies

UAVs can be equipped with numerous sensors mounted on board, even more than dozens of sensors depending on the class of drone and the application required by the mission.
Some sensors are used to acquire data with the sole purpose of controlling the platform during navigation, such as velocimeters, gauges, inertial/angular measurement devices and even imaging sensors for Simultaneous Localization and Mapping (SLAM)[1]. Therefore, considering that such sensors are specifically dedicated to navigation, they are not properly considered part of the remote sensing system, but are fundamental for the success of the operations.
Alongside these vital sensors, there are all the sensors needed for the specific application, that allow you to meet the objectives of the mission. Thus, for example, where required by the mission, drones, equipped with accelerometers, magnetometers, gyroscopes (IMU), GPS, altimeters and cameras (optical, thermal, multispectral or

[1]Simultaneous Localization and Mapping (SLAM) technology allows a device to position and navigate in a certain space based on its surroundings

hyperspectral), associate each image to the corresponding position of the GPS, to the altitude of the UAV and its orientation (pitch, roll and yaw angles), with the aim of obtaining 3D mapping, georeferenced images and orthophotos.
In Table 4.4, the different sensors and instruments that may be present on board the UAVs are listed.

Auxiliary sensors	Specific sensors
• GPS • IMU • Gyroscopes • Accelerometers • Altimeters • Video stabilizer • Image transmitter • Communication antennas (VHF, UHF) • Communication modems	• Video cameras (visible spectrum) • Thermal cameras • Infrared cameras • FLIR • LIDAR (Laser scanner) • Multi-Hyperspectral (Hyper UAS) • Irradiance • Radar / SAR • Radiometer (multi-frequency) • Infrared spectroscopy • Ultraviolet spectrometer • Multi-gas detector • Sonar • Particle counters (optical, condensation) • Photometer, aethalometer • Aerosol sampling • Probes (temperature, humidity, pressure) • Cloud droplet spectrometer • Pyranometer • Magnetic sensor

Table 4.4. On-board sensors

4.2 Possible solutions for OSP application

As the last step of the thesis work, a literature review is illustrated, presenting the possible solutions and configurations to collect data remotely on UAV platform and that can potentially be employed for OSP application.

4.2.1 UAV equipped with cameras/video-cameras

As SHM applications usually start by measuring structural dynamic response but the measurement of the displacement is limited by several challenges, such as high cost, low accuracy and fixed reference point request, researchers recently have carried out several interesting studies on vision-based monitoring of structural health, which produce efficient non-contact measurements.

Unfortunately, these approaches have some limitation due to stationary cameras and the difficulty in finding a proper location to deploy them, in term of appropriate line-of- sight, especially when it is needed to monitor critical civil infrastructures.

Yoon et al. [21] develop an alternative approach to overcome the aforementioned issues: they use an UAV equipped with commercial video-cameras to collect structural displacement measurements; in particular this approach enables the estimation of absolute structural displacement employing only a single drone.
The implemented method is the following [21]:

- *target-free relative displacement measurement*: firstly a target-free method is realized to obtain the relative displacement of the structure from the video;
- *6 Degree-of-Freedom (DOF) camera motion estimation*: three translations and three rotations are determined by tracking background feature points;
- *recovering structural absolute displacement*: relative structural displacement and camera motion are combined to determine the absolute displacement.

In addition, Yoon et al. validate this approach carrying out laboratory experiment: a motion simulator was used to reproduce the displacement of a bridge under train traffic. That set up revealed that the proposed approach can estimate the absolute displacement of structures with reasonable accuracy.
Regarding the thesis case study, for the optimal sensor placement, it is necessary to measure the structural displacement of the structure in ambient vibration; thus, it would be necessary to understand if it is possible to use the same approach through simulations and experiments.
Additionally, in this framework, future research areas could include, for instance, data fusion techniques (IMU sensors) and multiple cameras usage for measuring structural out-of-plane motion.

An other approach is the one presented by Brandon et al. [22]: a novel remote sensing technique is developed to measure three-component dynamic displacement of 3D structures. In particular, a sensing system involves the use of an UAV platform and contact-free sensors, as optical and infrared (IR) cameras. This set up provides a convenient portable alternative with respect to conventional approaches requiring installation of sensors on the structure. This study includes:

- integration of both optical and IR cameras with the UAV to measure dynamic response of the structure;

- development of new data post-processing algorithms to extract the 3-components displacement simultaneously from optical and IR videos. This feature represents a peculiar advantage compared to the UAV-based techniques for displacement measurement that allow the measurements in only one or two directions using optical cameras or laser sensors.

In this research, however, as the UAV hover stably in the air to acquire high-quality images, there is a slight drifting of the drone that could potentially introduce significant errors when used for dynamically sensitive application, because of the movement of the UAV being added to the measurements themselves. To cancel those errors, the UAV has to be *self-aware* in all three directions: thus, self-awareness is achieved by measuring UAV relative displacements with respect to stationary references, so that the drone's motion can be removed.
To prove the concept, Brandon et al. carried out an experiment using an DJI Mavic 2 Pro equipped with an Intel Realsense D435, with integrated IR sensors,optical RGB camera, and a projector. The experimental results showed that [22] maximum frequency and damping estimation errors in the experiments are 3.5% and 4.4%, and the root-mean-square error is less than 2-mm: finally, using this technique, the measurement accuracy achieved is sufficient for SHM application to civil structures, where, usually, an error of few percent in the frequency and in damping estimation are expected).

4.2.2 UAV equipped with Laser Doppler Vibrometer

On the other hand, Garg et al. [23] proposed an UAS equipped with a Laser Doppler Vibrometer (LDV) for measuring dynamic displacement of a bridge under train loading, validating and developing a system thanks to several experiments.
LDV works on the principle of interferometry: the reference and reflected beam interfere causing light and dark pattern, that can be used to evaluate the transverse displacement of the target. For a static arrangement, the vibrometer measures the exact vibration, only if its signal is perpendicular to the target; otherwise, the signal is reduced by the cosine component of the angle.
Garg et al. performed several tests, selecting DJI Matrice 600 Pro with a payload capability of 5.5 kg as platform and using a shake table for simulating the vibration of a railroad bridge under train crossing.
During tests, LDV was positioned under the UAV and the integrated system measured the dynamic transverse displacements of the target.
From these tests, the average of the peak errors maximum, for the three successful trials, results 10% and the average of the RMS difference results 8%.
t can be concluded that an UAV-LDV system can measure the target dynamic

transverse displacements.
Regarding the case study of this thesis, again, it is necessary to obtain displacement data of the structure in ambient vibration; thus, if this approach is used, it will be mandatory to perform simulation and experiments, selecting the suitable set up in term of sensors and drone performances.

Chapter 5

Conclusion & Recommendations

This work of thesis proposed an analysis of the possible platforms to be used to remotely collect data as input for Optimal Sensor Placement for Structural Health Monitoring of structures and infrastructures.
In fact, the need of monitoring and evaluating the health of structures imposes the need of mounting sensors on the monitored structure. However, sensors can be placed only in a finite number of locations and the number of sensors is limited; thus, given this limitation, sensors locations have to be optimized. Nevertheless, current OSP strategy have several challenges due to discrepancy errors (for virtualization-based method) or accessibility issues, difficulty in dynamic identification, and issue with direction of acquisition (for SI approach).
In this framework, Remote Sensing was introduced as an alternative that can overcome the aforementioned challenges.
After a state of the art of RS principles and technology, OSP requirements have been identified and a selection process, through the use of Analytical Hierarchy Process, was illustrated to recognize the most suitable solution by ordering the alternatives according to an axis of preference. AHP allows to identify the main attributes with the relative importance weights and to draw up a ranking of the solutions based on how well they meet the requirements with respect to the weighted attributes. Therefore, by the analysis of requirements and the use of AHP, the Unmanned Aerial Vehicle was chosen as remote sensing platform to collect the required measurements. However, during the selection process, the results showed that immediately behind the UAV platform, according to the weights of the attributes, there were in second place of preference the ground-borne platforms. Therefore, it is suggested, in the future, to analyze a hybrid platform solution that involves the combined use of a UAV, equipped with adequate sensors, supported by a suitable ground system.
Afterwards, a general overview of UAV and possible configuration from literature

were presented: in particular, UAV equipped with optical and infrared sensor and UAV equipped with Laser Doppler Vibrometer could potentially be further explored and tested to validate the application of these configuration to the case study, selecting the suitable set up in term of type of drone and type and number of sensors. Note that the selection methodology used for the platform selection can be easily applied for any other selection, such as the most suitable UAV-sensors configuration.

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Glossary

AHP Analytical Hierarchy Process. III, 33–35, 61

FE Finite Element. VIII, 30

FoM Figures of Merit. 34

GSD Ground Sampling Distance. 41

InSAR Interferometric Synthetic Aperture Radar. III, 19–21

IR Infrared. 58

LDV Laser Doppler Vibrometer. 22, 23, 59

LiDAR Light Detection And Ranging. III, 21, 22, 53

LOS Line Of Sight. 21

MCDA Multi-Criteria Decision Analysis. 33

OSP Optimal Sensor Placement. VIII, 1, 2, 29–31, 43, 57, 61

RPA Remotely Piloted Aircraft. 39

RS Remote Sensing. VIII, 1–3, 61

SAR Synthetic Aperture Radar. 17–20

SHM Structural Health Monitoring. VIII, 1, 28, 29, 57, 59

SI System Identification. 30, 61

TIR Thermal Infrared. 17

UAS Unmanned Air Vehicle. 38, 39, 45, 59

UAV Unmanned Aerial Vehicle. III, 2, 22, 39, 45, 49, 51, 53, 55–59, 61, 62

VTOL Vertical Take-Off and Landing. 49