POLITECNICO DI TORINO

MASTER'S DEGREE IN AEROSPACE ENGINEERING

MASTER'S DEGREE THESIS

Safety assessment for fixed-wing UAVs for remote sensing applications: Turin Case study

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December, 2024

Abstract

Large amounts of greenhouse gas emissions come from residential, industrial and commercial buildings in urban areas. Consequently, decarbonisation plans and design solutions must be implemented to reduce emissions. In this context, the thesis proposes an aerial thermal infrared remote sensing mission concept for detecting building heat losses, inspired by a previous study on energy demand estimation using thermal images regarding the city of Turin. Thermal imaging applications can be carried out by equipping aircraft, drones or satellites, depending on the level of detail required, with cameras capable of collecting emitted infrared radiation. Specifically, the proposed mission is conceived for a fixed-wing unmanned aerial vehicle (UAV), comparable in size to a small general aviation aircraft.

The thesis is developed according to a multi-step process that includes two main parts: the case study definition and a preliminary aircraft safety assessment. While the first part recalls methodological aspects of mission design, the second part illustrates an approach to aircraft safety typical of the initial design phases. The process begins by defining the mission statement and continues with a stakeholder analysis. Subsequently, mission objectives and high-level requirements are derived and a trade-off analysis of possible thermal infrared camera options is performed. In addition, a brief market overview of thermal imaging systems and UAVs is presented. The first part of the process ends by characterising the mission and payload in operational terms. In particular, the flight operations are described graphically with a basic concept of operations on which the subsequent calculation of thermal infrared camera performance and image acquisition phase time is based. This calculation, which includes a parametric analysis, is performed using a code created specifically for the case study.

The core of the second part of the process is a functional analysis which provides several results. First, the unmanned aircraft system (UAS) functional tree, which includes the UAV functional tree, is developed for the case study. Specifically, only the functions of the UAV are shown in detail in the thesis. Once these functions are determined, they are matched to the products able to perform them, obtaining the functions/products matrices. These products are then grouped to create the UAV product tree, useful for drawing a UAV conceptual design sketch to describe the hypothetical aircraft archi tecture. After, an aircraft functional hazard assessment is conducted, giving as input

the identified functions, to determine the failure conditions associated. Considering that the mission is a civil application, for the classification of failure conditions and the allocation of safety requirements the JARUS AMC RPAS.1309 is applied as the regulatory reference. By combining functional analysis and hazard assessment results, a preliminary aircraft fault tree is finally proposed to study the higher-level causes that could lead to the loss of the UAV.
In conclusion, the thesis is a baseline study that lays the groundwork for future missions in different urban environments, achievable with existing or next-generation UAVs. Secondly, the initial safety assessment constitutes a starting point in designing a new mission-oriented UAV concept, compliant with the safety regulations for certification.

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Acronyms

AFHA Aircraft Functional Hazard Assessment

AFTA Aircraft Fault Tree Analysis

AHP Analytical Hierarchy Process

AMC Acceptable Means of Compliance

COTS Commercial Off-The-Shelf

CS Certification Specification

EASA European Union Aviation Safety Agency

ENAC Ente Nazionale per l'Aviazione Civile

ENAV Ente Nazionale di Assistenza al Volo

EO Earth Observation

FHA Functional Hazard Assessment

FIR Far-Infrared

FTA Fault Tree Analysis

FOM Figure Of Merit

GCS Ground Control Station

HSI Hyperspectral Imager

ICAO International Civil Aviation Organization

IR Infrared

JARUS Joint Authorities for Rulemaking of Unmanned Systems

LiDAR Light Detection And Ranging

LOS	Line Of Sight
LWIR	Long Wavelength Infrared
MALE	Medium Altitude Long Endurance
MATLAB	MATrix LABoratory
MODTRAN	MODerate resolution atmospheric TRANsmission
MR	Medium Range
MSI	Multispectral Imager
MWIR	Medium Wavelength Infrared
NASA	National Aeronautics and Space Administration
NIR	Near Infrared
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
SAE	Society of Automotive Engineers
SMAT - F1	Sistema di Monitoraggio Avanzato del Territorio - Fase 1
SWIR	Short Wavelength Infrared
TI	Thermal Imager
TIR	Thermal Infrared
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
VI	Value Index
WF	Weight Factor

1 | Introduction

1.1 The role of aerial thermal infrared remote sensing in the decarbonisation process of cities

The operational use of aircraft or UAVs to carry out aerial (or airborne) remote sensing missions for scientific purposes represents the new frontier of Earth Observation (EO). EO is performed thanks to sophisticated and expensive cameras, which interact passively or actively with the observed objects, to detect certain wavelengths of the electromagnetic spectrum. The information gathered from the sensors is then processed to obtain different types of images, which experts can analyse. In particular, remote sensing is a well-known technique in the space field where satellites are equipped with specific payloads for this type of application. Remote sensing, as reported in [1], is employed in many contexts such as meteorology, oceanography, geology, cartography and environmental monitoring.
In this thesis, a civil application of aerial thermal infrared (TIR) remote sensing (or aerial thermography) on an urban scale is considered. Thermography, as reported in [2], can be carried out at the microscale, district or city level and territorial scale to capture aerial thermographic data (i.e., images in the infrared region); the choice of using an aircraft, UAV or satellite, therefore, depends on the size of the image acquisition area. The mission goal is to identify heat losses by analysing thermal infrared images of buildings obtained by detecting TIR radiation.[1] It is then possible to evaluate the energy impact, especially relating to old buildings, and plan modernisation interventions (e.g., the installation of photovoltaic panels) to reduce consumption and carbon dioxide emissions [2].
Cities are a target of the decarbonisation process as they are responsible for over 70% of global CO_2 emissions [3]. Population growth causes an increase in energy demand, which consequently leads to higher greenhouse gas emissions [2]. For this reason, it is important to define new environmental policies for the sustainable development of

[1] The temperature of building surfaces is considered an indicator of thermal losses [2].

urban areas. As reported in [2], the European Union's goal is to reduce greenhouse gas emissions by 55% by 2030, to reach 80 - 95% by 2050. Turin, where 37.2% of carbon dioxide emissions come from residential areas, is one of the candidate cities to achieve climate neutrality by 2030 [2].
A thermographic study regarding a part of the Barriera di Milano district (Turin) has already been conducted [2]. This study represents the first step towards the final goal of generating a digital twin of the entire city thanks to thermographic acquisitions and three-dimensional LiDAR images of buildings.

Figure 1.1. Example of aerial thermal infrared image [2].

2 | Case study definition

The following paragraphs describe the thesis process, shown in Figure 2.1, which has been conceived by adapting the methodologies reported in the publications [4], [5] and [6]. Specifically, the thesis includes two main parts:

- the *case study definition*, which illustrates mission-related aspects, and
- the *preliminary aircraft safety assessment*, which addresses safety aspects at the aircraft level.

The proposed scheme is divided into several steps. First of all, the *mission statement* is defined. Based on this, a *stakeholder analysis* is performed, the *mission objectives* are identified and *high-level requirements* are determined. Subsequently, a separate *camera trade-off analysis* is conducted. Lastly, the first part of the diagram ends with the *definition of mission and payload* from a strictly operational point of view.
The process continues with *functional analysis*, which leads to the definition of the *UAV conceptual design*. The results of this analysis can also be used to carry out an *Aircraft Functional Hazard Assessment* (AFHA) and, in conclusion, create a *preliminary aircraft fault tree*.

2.1 Mission statement

The mission statement clearly and concisely describes the high-level goal of the mission (i.e., why it is necessary) [7]. The statement proposed for the case study is the following:

> *"The mission is part of a project involving a fixed-wing UAV in an urban remote sensing application to obtain thermal infrared images of buildings, useful to identify heat losses for energy efficiency and decarbonisation studies regarding the city of Turin, which aims to achieve carbon neutrality by 2030".*

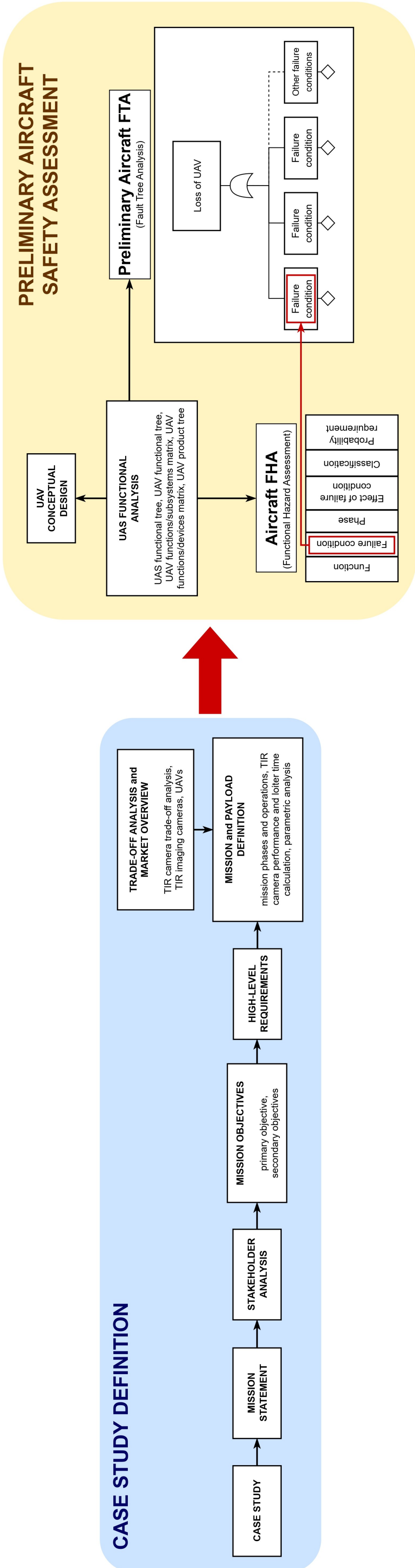

Figure 2.1. Thesis process.

2.2 Stakeholder analysis and mission objectives

The stakeholder analysis is the next step in the case study definition process. Taking into account the mission statement defined above, it is important to establish who may be involved in the mission and therefore benefit from its accomplishment [7]. In particular, the expectations of stakeholders are summarised in the secondary objectives (see Attachments).
Mission objectives include both primary and secondary objectives. The primary objective is an overall objective determined directly from the mission statement, while secondary objectives are more targeted and are derived for each identified category of stakeholder through stakeholder analysis. The categories (Table 2.1) have been created according to [7] and [8], taking into account the mission features.
The primary objective is defined as follows:

> *"To perform a city-scale thermal infrared remote sensing mission using a fixed-wing UAV".*

In addition, the identified stakeholders are listed below:

- *universities*;
- *scientific community*;
- *research centers*;
- *governments*;
- *environmental organisations*;
- *industries/enterprises*;
- *energy companies*;
- *inhabitants*;
- *mission developers*;
- *UAS manufacturer/owner*;
- *mission operators*;
- *urban planners*;
- *architects*;
- *designers*;
- *engineers*;
- *environmental policy-makers.*

2.3 High-level requirements

Requirements are established at each stage of a project, as the level of detail grows, and their definition is an iterative process since a design change requires a change in requirements (introduction, elimination or modification of a requirement).
Different types of requirements can be set [7]:

CATEGORY LEGEND	
END USER	The end user is the one who uses the raw or processed output data for different purposes or benefits from the results of the mission (that is part of a project).
CUSTOMER	The customer is the one who purchases the processed project results or requests a specific service to obtain certain data.
SPONSOR	The sponsor is the one who finances the project and consequently the mission.
DEVELOPER	The developer is the one who is responsible for designing the mission in all its parts, defining how it will be carried out.
SUPPLIER	The supplier is the one who is responsible for providing the UAS (Unmanned Aircraft System) necessary to carry out the mission. The term "System" includes the vehicle, the ground control station and any other element that allows the correct execution of the mission.
OPERATOR	The operator is the one who is responsible to carry out the mission and therefore to ensure that it is carried out successfully. The term also includes anyone who is involved in the mission and contributes to its accomplishment.

Table 2.1. Categories of stakeholders.

- mission requirements;
- functional requirements;
- performance requirements;
- configuration requirements;
- interface requirements;
- design requirements;
- physical requirements;
- environmental requirements;
- operational requirements;
- product assurance requirements;
- safety requirements;
- logistics support requirements;
- human factors requirements;
- constraints from the regulatory framework.

Requirements must be correct, complete, unambiguous and verifiable in some way, otherwise they are unusable statements [7]. In particular, high-level requirements are the first to be set as they rigorously describe the mission statement and objectives [7]. The full list of identified high-level requirements is shown in Attachments. These are divided according to the types of requirements in Table 2.2. Specifically, the requirements are expressed in the "shall" form, as suggested in [6].
In conclusion, it is important to note that the defined requirements are not intended as definitive, but can be modified and updated as the project evolves. In addition, other external requirements may be added in later revisions of the project.

TYPE OF REQUIREMENT	
MIS	Mission
CON	Configuration
FUN	Functional
DES	Design
SAF	Safety
OPE	Operational
ENV	Environmental
PHY	Physical

Table 2.2. Types of requirements.

2.4 Trade-off analysis and market overview

As highlighted in the high-level requirements, the mission mainly requires a UAV and a thermal infrared camera. Therefore, the following section propose a trade-off analysis based on the information collected about thermal infrared cameras. In addition, a brief market overview of cameras and unmanned aircraft potentially suitable for the case study is provided. Before discussing the analysis in detail, some important concepts such as infrared radiation and hyperspectral imaging are introduced to better understand the topic.

2.4.1 Introduction to thermal infrared imaging

Infrared radiation (0.75 μm - 1000 μm) is the region of the electromagnetic spectrum between visible light and microwaves [9]. All objects emit in this band, but only specific ranges are studied using the cameras available. In particular, infrared cameras are passive systems because they do not require an artificial energy source to illuminate objects [10].
Infrared radiation emitted by distant objects is detected in thermal imaging (or thermography) [9]; in this technique, the sensors can collect the radiation which is then translated into images (during the processing phase) to distinguish the different temperatures of an observed scene.
According to [11], four main bands are used for remote sensing applications (Figure 2.2). These bands are then divided into reflected infrared (NIR, SWIR) and thermal/emitted infrared (MWIR, LWIR) [12]. NIR and SWIR are associated with reflected solar radiation; MWIR (3 μm - 5 μm) and LWIR (8 μm - 14 μm) represent the radiation emitted by the earth, objects and the atmosphere. As a result, TIR radiation can be detected both day and night, compared to reflected radiation, allowing nighttime thermal imaging [13].

In the field of thermal infrared remote sensing, the reference laws are the *Stefan-Boltzmann law* and the *Wien's displacement law* [14]. The first law (Equation 2.1)

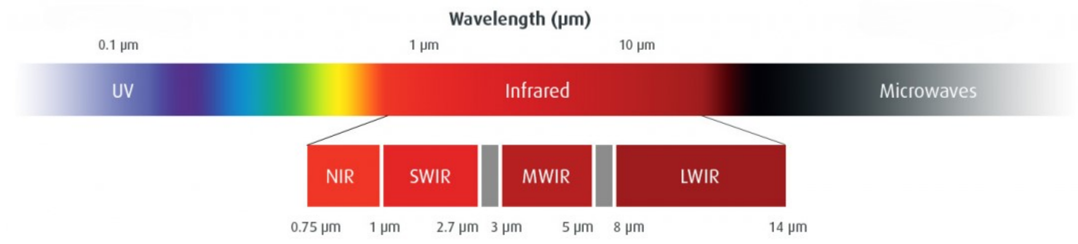

Figure 2.2. IR region [15].

defines the concept of *radiant flux* (F_r) of an object as the product of its *emissivity* (ϵ), the *Stefan-Boltzmann constant* (σ) and its *kinetic temperature* (T_{kin}) [11]:

$$F_r = \epsilon \cdot \sigma \cdot T_{kin}^4 \quad [W/m^2] \tag{2.1}$$

As reported in [11], the radiant flux represents the electromagnetic energy radiated from a material and the *radiant temperature* (T_{rad}) is the concentration of radiant flux. On the other hand, the kinetic temperature is the concentration of kinetic heat. In particular, kinetic heat (or internal heat) of a material is the energy associated with the random movement of particles which due to collisions change their energetic state and emit electromagnetic radiation at the surface level. This energy then becomes radiant energy. Two different temperatures are thus identified: the kinetic temperature, which is measured using a thermometer in contact with the body, and the radiant temperature, which is detected remotely by a radiometer. As a result, the temperature measured by the sensor on board the aircraft differs from the actual temperature of an observed object. However, radiant temperature is considered a good approximation of the kinetic temperature of a body since, in general, the two temperatures are well correlated [16]. This condition thus justifies the use of thermal infrared remote sensing. Specifically, the radiant temperature is always lower than the kinetic temperature according to the following equation:

$$T_{rad} = \epsilon^{1/4} \cdot T_{kin} \quad [K] \tag{2.2}$$

As can be seen, the difference between the two temperatures depends on emissivity, which is always less than 1 for any object that is not a blackbody. For example, the measured radiant temperatures of nearby bodies could be different despite their kinetic temperatures are identical [16]. The emissivity, defined as the ratio between the radiant flux of a material and that of a blackbody at the same temperature, is a thermal property which changes according to the wavelength considered and indicates the ability of an object to radiate energy. It also expresses the ability to absorb energy, indeed, objects with high emissivity can absorb and radiate lots of energy, while the opposite

happens for objects with low emissivity (the ability to absorb and radiate energy is reduced). Low absorption is also associated with high reflectivity; this condition explains, for example, why metal roofs (such as those made of aluminium) appear cold, and thus dark, in both day and night thermal infrared images [16]. These roofs have a cold radiant temperature [11] because they reflect much of the incident radiation. In general, the brightest objects shown in thermal infrared images are the hottest (i.e., they have a higher radiant temperature), while the darkest ones are the coolest [11].
It is important to specify that many thermal infrared systems detect the radiant temperature of an object rather than the flux [11]. Therefore, if the emissivity is known, the kinetic temperature of a material can be derived, while if the kinetic and radiant temperatures are known, the emissivity can be calculated [16].
However, emissivity is not the only reason why the actual temperature of an object is different from the measured one. In fact, in TIR remote sensing, the radiant energy captured by a sensor (i.e., the radiant flux) consists of both emitted and reflected TIR radiation [17]. Figure 2.3 shows the radiation contributions reaching the sensor. The downwelling radiance impacts the observed target which reflects it. This radiant flux is then attenuated by the atmosphere as the self-emitted one. The contribution of unwanted radiation is therefore a problem for airborne TIR remote sensing and it cannot be neglected when precisely determining the temperature of a ground target.
In conclusion, other material parameters which affect TIR remote sensing are thermal inertia, thermal capacity and thermal conductivity. Daytime solar heating (which affects the kinetic and radiant temperatures of materials), weather and terrain conditions must also be taken into account [11].

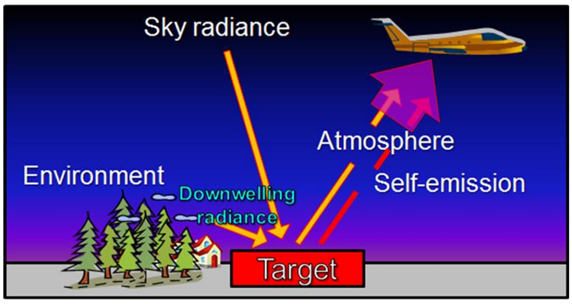

Figure 2.3. TIR radiation contributions [17].

The second law explains the inversely proportional relationship between the peak of radiant energy emitted by a blackbody (i.e., the peak or *dominant wavelength* (λ_{max}) at which the radiated energy is maximum) and the temperature of the body itself [11]:

$$\lambda_{max} = \frac{2898\ \mu m \cdot K}{T_{rad}\ [K]} \tag{2.3}$$

In particular, as the temperature increases, the radiated energy increases consequently and the dominant wavelength moves to lower values (i.e., shorter wavelengths) [11], as shown in Figure 2.4.
The Equation 2.3 can be applied to determine λ_{max} of any object [16] and, therefore, it is useful to find the best wavelength band for remote sensing purposes. Thus, the measuring temperature is clearly a significant parameter for choosing the most suitable camera [18].

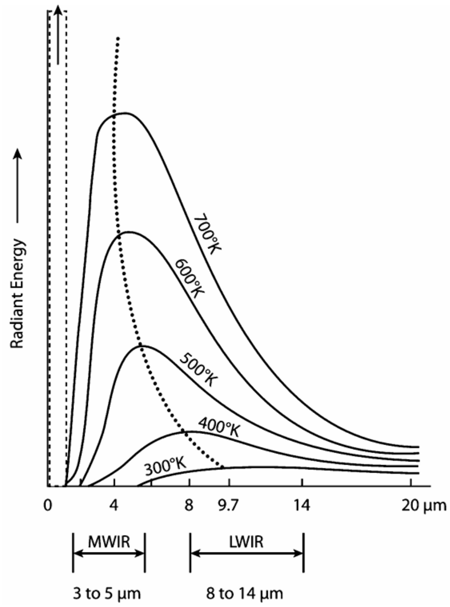

Figure 2.4. Radiant energy curves and peaks (dotted line) for objects at certain temperatures [11].

Figure 2.5 shows the relationship between the measuring temperature and the wavelength. Based on this figure, MWIR and LWIR are both appropriate bands for the case study since they are sensitive to low temperatures.[1] Indeed, as illustrated in [16], studying heat losses and insulation of residential heated buildings is one of the main applications of airborne TIR remote sensing.

2.4.2 Hyperspectral imaging

For the proposed mission, the idea is to use a hyperspectral TIR camera rather than a conventional one (see the case study presented in [2]), to explore the potential of hyperspectral imaging (i.e., a technique for obtaining images with high spectral resolution). This type of imaging allows the detection of electromagnetic radiation (reflected or emitted) over many narrow and closely spaced spectral bands (so that the spectra

[1] Longer wavelengths are therefore needed to measure lower temperatures.

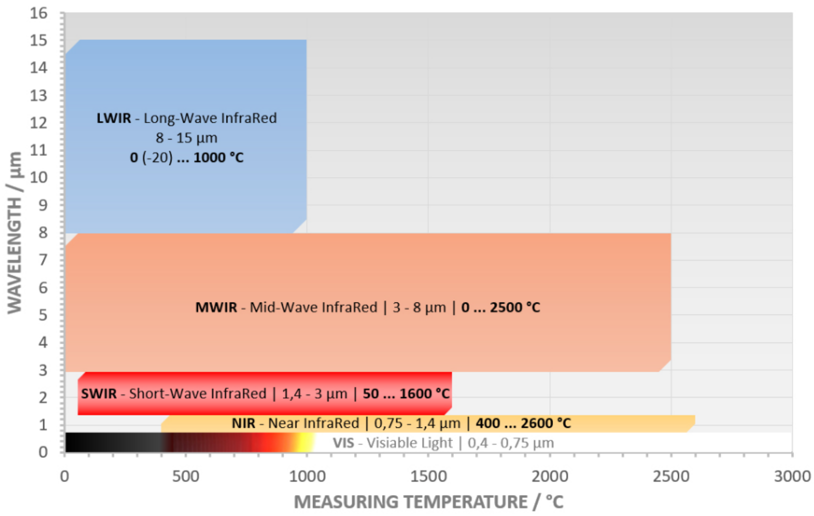

Figure 2.5. Measuring temperature vs. wavelength [18].

obtained are continuous) to evaluate the chemical nature and physical properties of the observed objects [19].
This technology has shown significant development in recent years, both in space and aerial remote sensing. Space use is a good solution for covering large areas, while UAVs represent an alternative when looking for better spatial resolution, lower costs and greater versatility [20]. Table 2.3 shows several uses of hyperspectral imaging for different spectral regions. As can be seen, most applications are in the infrared band.

Spectral region	Spectral range (nm)	Optimal observations
Thermal Infrared (TIR)	8000 - 15000	Heat sources, land and sea surface temperatures, geothermal mapping, thermal surveys.
Infrared (IR)	6000 - 7000	Water vapour, soil moisture, cloud cover, thermography, forest fires and hotspots.
Mid-wave Infrared (MIR)	3000 - 5000	Mineral and soil mapping, sea surface temperature, ice formations, geothermal and volcanic activity.
Short-wave Infrared (SWIR)	1100 - 3000	Vegetation mapping, dynamics and physiology, cloud and rock type.
Near Infrared (NIR)	700 - 1100	Vegetation vigour, crop and soil moisture, rock and mineral type.
Visible	400 - 700	Shallow coastal and coral reef bathymetry, vegetation type, land cover, urban development, ocean colour.
Ultraviolet (UV)	100 - 400	Ozone concentration, coral reef health, aerosol distribution, pollution.

Table 2.3. Examples of hyperspectral imaging applications [19].

Hyperspectral cameras are passive systems. For this reason, those operating in the reflected infrared can only work during the day, when the sun illuminates the objects [20], while those working in the thermal infrared can also be used at night [21].
An image obtained through a hyperspectral sensor has two spatial dimensions and one

spectral dimension, as shown in Figure 2.6. Specifically, it is composed of a set of 2D images, each referring to a certain spectral band, stacked to create the so-called spectral cube (Figure 2.7), a sort of 3D image [19]. From the spectral cube, it is possible to derive a spectral curve for each image pixel, that includes each wavelength considered [19]. These curves are critical for studying the unique spectral reflectance or emissivity signatures of materials. In particular, the reflectance of an object is the effectiveness in reflecting radiant energy [22], while emissivity is the effectiveness in emitting energy as thermal radiation [23].

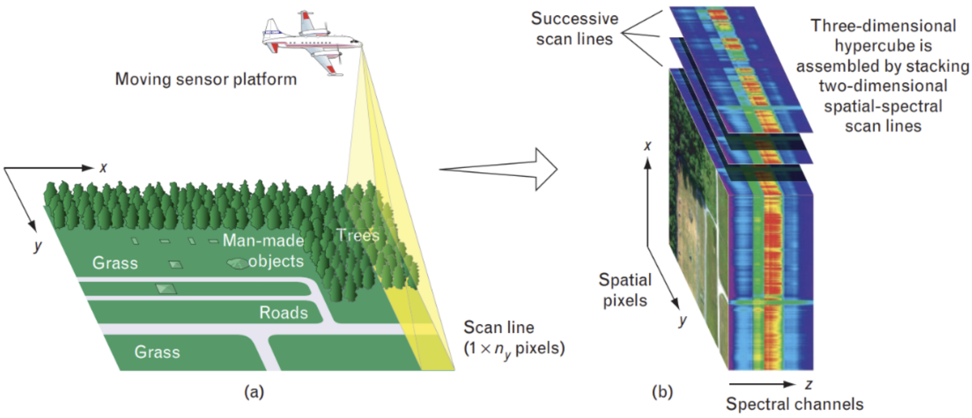

Figure 2.6. Hyperspectral imaging technique [19].

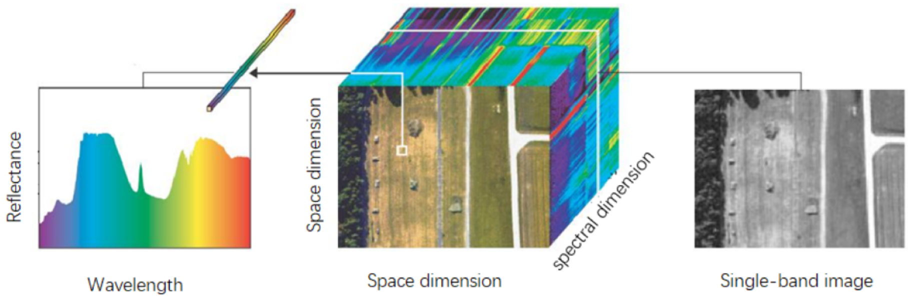

Figure 2.7. Hyperspectral image cube [19].

Hyperspectral and multispectral imaging are different in terms of number and width of spectral bands (spectral channels) [24]. Multispectral imagers (MSI) can detect radiation using only a smaller number of bands, which are also wider [19]. For example, in space field observation, they work with 3-50 relatively wide bands, while hyperspectral imagers (HSI) have 30-300 bands (usually less than 10 nm narrow [19]) available with higher spectral resolution [10].

2.4.3 Comparison between MWIR and LWIR

Some considerations are now presented on the atmospheric transmission of infrared radiation and the use of MWIR and LWIR bands in particular environmental conditions. Since the mission may not be performed in optimal weather conditions, a thermal infrared camera capable of providing the best performance is required.
The transmission of infrared radiation through the atmosphere changes depending on the wavelength [11]. As a result, only certain regions are suitable for thermal infrared imaging [16]. As shown in Figure 2.8, atmospheric windows allow radiant energy to pass through, while absorption bands absorb the radiation completely or almost completely. Specifically, atmospheric absorption is caused mainly by carbon dioxide (CO_2), water vapour (H_2O) and ozone (O_3), therefore, it is critical when the sensor is located far from the source emitting radiation because the path to travel is longer.
According to Figure 2.8, the LWIR band is generally less affected by atmospheric absorption. In addition, considering that the flight altitude of aircraft and UAVs is clearly below the ozone layer, TIR remote sensing can be performed by covering the entire LWIR band [11].

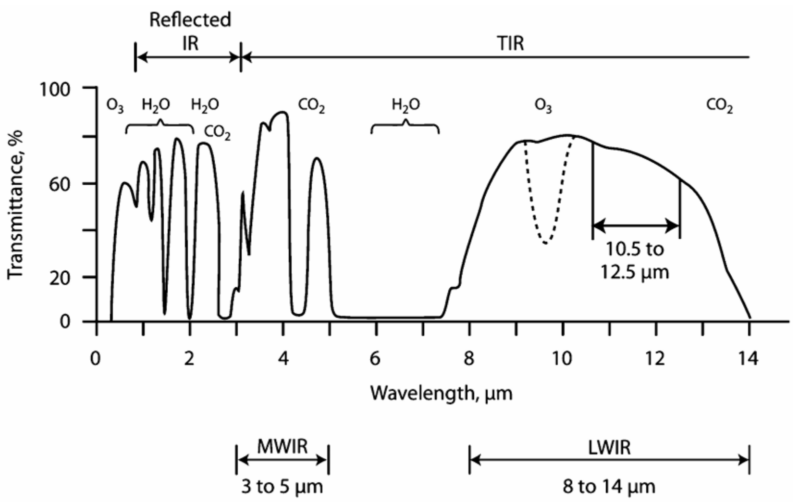

Figure 2.8. Atmospheric windows for reflected IR and TIR [11].

With reference to [25], the performance of MWIR and LWIR bands through fog and rain in the context of thermal imaging is discussed below.
The information given should be taken into account when selecting a sensor, especially in the case of the city of Turin which is affected by smog and fog during autumn and winter. Therefore, since the case study requires performing the mission on different days of the year and at different times of the day (even at night), to obtain a large database for subsequent comparative analysis, it is important to know the atmosphere attenuation even in adverse weather conditions.

Due to atmospheric absorption and scattering caused by particles (aerosols), fog and rain reduce the distance at which it is possible to detect radiation from an object (i.e., they affect the ability to capture changes in infrared radiation) [25].
For example, in the case of excellent visibility conditions, the lower humidity in winter allows a longer detection distance than in summer (typically characterised by a more humid climate) [25]. In addition, the type and size (diameter) of the aerosols (e.g., water particles) determine the attenuation of the detected thermal radiation, which is more intense if the diameter is larger [25].
Although atmospheric transmission and conditions are important factors in establishing the detection distance for a thermal imaging camera, many other factors must be considered such as the lens used, cooling, sensitivity, target size, target temperature and background temperature [25]. It is then significant to note that low spatial resolution, detector noise and signal processing negatively affect target-background thermal contrast by reducing it [25].
Three examples of atmospheric transmission results obtained with MODTRAN (for different application ranges) are reported from [25] to show the different behaviour of MWIR and LWIR bands.
This code allows for the modelling and simulation of different atmospheric conditions for evaluating the infrared radiation passing through the atmosphere, starting from the definition of the climate model and the type of atmospheric aerosol (Table 2.4). Aerosol can be defined as a suspension of water droplets or solid particles (such as particulate or sand) in the air [26]. Furthermore, the model takes into account the temperature and emissivity conditions of the scene and the observed object, the geometric and length characteristics of the radiation path and lastly visibility [25]. In conclusion, the distance at which IR radiation can be detected in foggy or rainy conditions depends on the climate and aerosol encountered; in particular, in the presence of urban aerosols, the achievable detection distances are greater because the particles have a smaller diameter compared to other aerosols [25].

Climate	Aerosol
Tropical	Rural
Midlatitude summer	Maritime
Midlatitude winter	Urban
Subarctic summer	Advection fog
Subarctic winter	Radiative fog
US Standard	Desert

Table 2.4. MODTRAN models and aerosol options [25].

In Figures 2.9 and 2.11, the MWIR and LWIR bands perform similarly, while in Figure 2.10, the LWIR band is far better than the MWIR.
A further improvement in performance in foggy conditions, for example, comes from

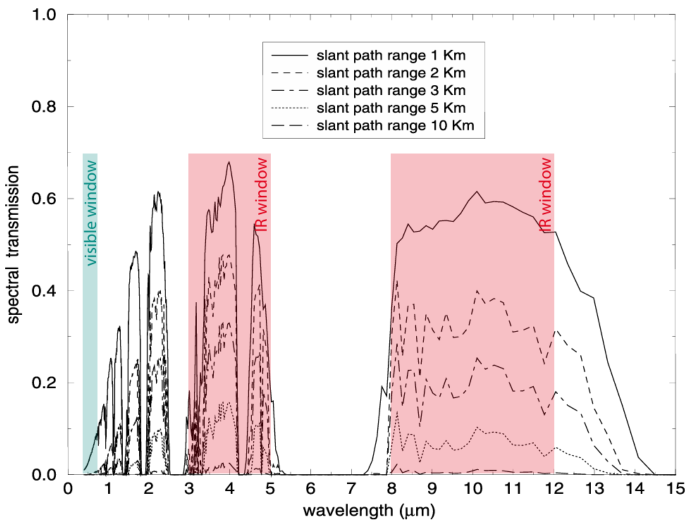

Figure 2.9. Spectral transmission (CAT I fog, midlatitude summer, rural aerosol) [25].

the use of cooled thermal imaging sensors (detectors) that improve the sensitivity in temperature measurements [25]. Uncooled sensors are typically employed in the LWIR band, while cooled ones are used in both MWIR and LWIR [25].
Table 2.5 shows some detection distance values in kilometres (in foggy conditions) for an MWIR camera and an LWIR camera, considering a target-background temperature difference of 10°C. In particular, distance ranges obtained using different climate and aerosol models are provided for CAT I only. In this case, the optimal conditions for LWIR detection are winter with low humidity and rural aerosols, while for MWIR detection are summer-like atmospheric conditions (i.e., high temperatures) [25].

Fog Category	MWIR	LWIR
Cat I	3.0 – 9.8	5.9 – 10.1
Cat II	0.54	2.4
Cat IIIa	0.294	0.293
Cat III c	0.089	0.087

Table 2.5. Examples of determined detection distances based on fog categories [25].

The table is proposed in [25] and globally shows a better behaviour of the LWIR camera when the fog is CAT[2] I and II. When the fog is very thick, however, the performance is equivalent. The results confirm the goodness of the LWIR band compared to MWIR when the detection takes place through fog, while in case of rain the performance is similar [25]. The penetration of MWIR is more limited by pollutants (gases and

[2] ICAO categories in terms of visual range for fog conditions (as reported in [25]): CAT I: 1220 m, CAT II: 610 m, CAT IIIa: 305 m, CAT IIIc: 92 m.

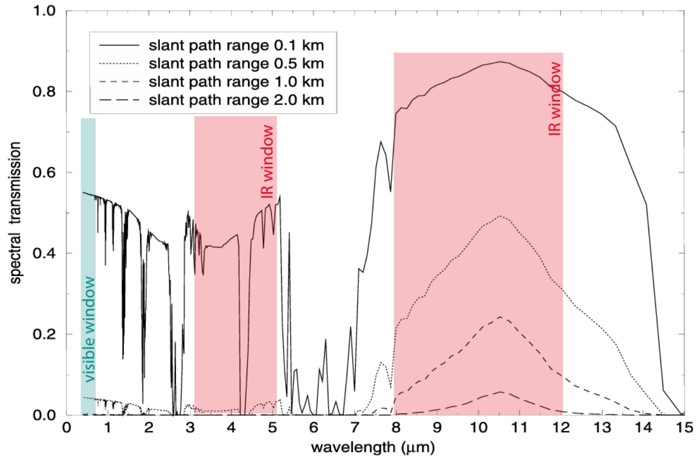

Figure 2.10. Spectral transmission (CAT II fog, midlatitude winter, radiative fog) [25].

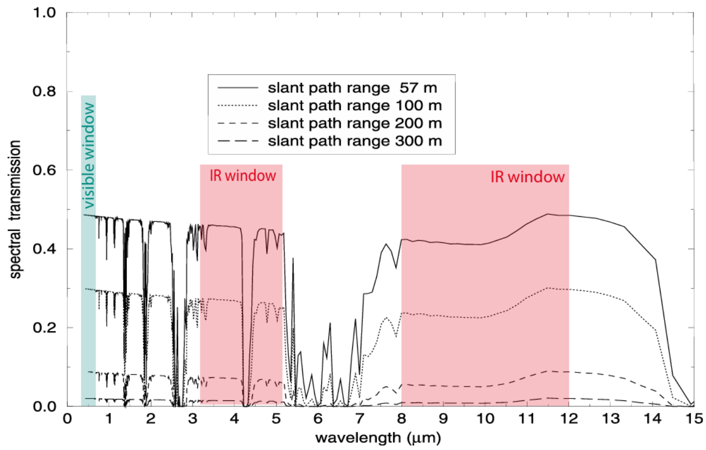

Figure 2.11. Spectral transmission (CAT IIIa fog, midlatitude winter, advection fog) [25].

particles), compared to LWIR, which alter the radiation along the path between object and sensor, worsening the contrast of the images [25]. Rain also affects contrast because the droplets absorb and disperse radiation and reduce lighting conditions [25].
The choice between MWIR and LWIR is also based on the climate of a certain geographical area, the atmospheric transmission, the temperature of sensed objects, the solar effects and the budget for a thermal imaging camera [27]. To conclude, relevant information about these bands is summarised in Tables 2.6 and 2.7.

Condition	Preferred band
High humidity	LWIR (<2.5km), MWIR (>2.5km)
Fog	LWIR
Arctic/sub-arctic	LWIR
Average climate	MWIR
Smoke/aerosols	LWIR
High temperature targets	MWIR
Very long range	MWIR

Table 2.6. Recommended bands for different conditions [27].

Factors	Notes
Climate	**LWIR** → for colder climates **MWIR** → for warmer climates
Solar effect	**LWIR** is less affected
Cost	Un-cooled **LWIR** cameras → very affordable, for short/mid-range applications Cooled **MWIR** cameras → expensive, for long-range surveillance Cooled **LWIR** cameras → very expensive, for long-range applications

Table 2.7. Factors to consider when choosing between MWIR and LWIR [27].

2.4.4 TIR camera trade-off analysis

The proposed trade-off analysis[3] is a qualitative and subjective analysis and should be seen as an initial preliminary judgment for following precise and in-depth quantitative analyses. It is useful to identify the most suitable type of TIR camera for remote sensing mission operations.
The trade-off focuses on four chosen alternatives:

- *MWIR camera*;
- *LWIR camera*;
- *hyperspectral MWIR camera*;
- *hyperspectral LWIR camera.*

In particular, the first two cameras can be intended as simple thermal imaging cameras. A trade-off is generally performed to compare different alternatives to choose the best one. For the case study, the analysis is based on methodology presented in [28] and is divided into the following steps:

[3] See Attachments.

1. Identification of alternatives.
2. Choice of *Figures Of Merit* (FOMs) and *drivers*.
3. Evaluation of *drivers*.
4. Evaluation of *ranks*.
5. Selection of *Weight Factors* (WFs).
6. Assignment of *scores* to alternatives.
7. Calculation of *Value Indices* (VIs) for each alternative.
8. Ranking of alternatives.

Specifically, FOMs are relevant parameters or characteristics associated with the different alternatives and are specified by defining the relative drivers. Weight factors are then assigned to each FOM to indicate the importance of each one compared to the others.
The parameters identified and considered important for the different camera options are listed below:

- *Performance*[4]:
  - *ground pixel size*;[5]
  - *spectral resolution/#spectral bands* (*channels*);
  - *detector pixels* (*#pixels*).
- *Environment*:
  - *atmospheric conditions*;
  - *operating temperature.*
- *Physical characteristics*:
  - *camera weight*;
  - *camera size.*
- *Cost*:

[4] See Appendix.
[5] Other terms used in the bibliographic references are ground resolution, spatial resolution and ground sample distance.

- *camera cost.*

The procedure to perform the trade-off begins with the determination of FOMs and their respective drivers.
After this, the so-called *correlation matrix* is created. It is filled column by column by comparing individually the column drivers with all the rows drivers. In particular, 1 is inserted in a cell if the column driver influences the row driver, otherwise, 0 is set.
Once the matrix is completed, the non-zero values of the rows can be added for each FOM to obtain the ranks. These values are then normalised with respect to the total, that is the sum of all the ranks evaluated.
At this point, WFs are defined for each FOM arranging them by columns so that each column has a weight value for each FOM.
The number of WFs that can be used is arbitrary, but it is clear that a greater number of combinations allows for a more accurate trade-off. In this analysis, the percentage rank values are taken as weight contributions, so they are all different. The second column contains all identical weights, while in the remaining columns the weight of a single FOM is set at 0.5. The same logic is then applied to the remaining columns. Considering that the sum of the weights of a single column must be equal to 1, the weights are defined dividing by 4, in the case of the second column of WFs, and dividing 0.5 by 3 in the remaining columns. It is significant to specify that the choice of weight values is discretionary, so other values could be used.
Subsequently, scores are assigned for each driver to each alternative according to two ad hoc scoring scales (Figure 2.12). Basically, a score indicates the goodness of a certain camera with respect to a specific driver. The first scoring scale considers values between 1 and 9 and is defined based on NASA AHP[6] Weighting Scale [29], while the second provides a score from 1 to 3. It is important to specify that the scoring is based on subjective judgment. Therefore, information has been collected and datasheets of different cameras have been consulted (Table 2.8, [30], [31]).
Finally, VIs are calculated for each alternative using the following equation[7]:

$$VI = \frac{w_p \cdot (d_{gps} + d_{spe} + d_{dp}) + w_e \cdot (d_{ac} + d_{ot})}{w_{pc} \cdot (d_{cw} + d_{cs}) + w_c \cdot d_{cc}} \tag{2.4}$$

where:

w_p = *Performance* WF;

w_e = *Environment* WF;

[6] *Analytical Hierarchy Process* (AHP) is a decision-making technique.
[7] In the equation, the drivers (d) represent the scores.

Scoring Scale	
9	Excellent
8	
7	Good
6	
5	Satisfactory
4	
3	Sufficient
2	
1	Insufficient

Scoring Scale	
3	Heavy/Big/Expensive
2	Average/Medium/Moderate
1	Light/Small/Cheap

Figure 2.12. Scoring scales.

w_{pc} = *Physical characteristics* WF;

w_c = *Cost* WF;

d_{gps} = *Ground pixel size* driver;

d_{spe} = *Spectral resolution/#spectral bands (channels)* driver;

d_{dp} = *Detector pixels (#pixels)* driver;

d_{ac} = *Atmospheric conditions* driver[8];

d_{ot} = *Operating temperature* driver[9];

d_{cw} = *Camera weight* driver;

d_{cs} = *Camera size* driver;

d_{cc} = *Camera cost* driver.

The numerator includes drivers whose improvement has a favourable (positive) effect on the value index, while the drivers at the denominator negatively affect the calculation. In conclusion, some significant remarks regarding the analysis are reported below:

- The trade-off is considered an iterative process, thus, it should be performed again following changes.
- The methodology presented is highly subjective. Consequently, because different opinions could influence the choices (and therefore the results), the analysis should be conducted by a team.

[8] It indicates the capability of the camera to operate in bad weather conditions (i.e., through fog and rain).
[9] It indicates the capability of the camera to operate at low operating temperatures.

- Expert opinion may be useful for the trade-off. The expert can suggest the best drivers, identify the wrong or missing ones, recommend the most appropriate scoring scales and provide advice on weight factors and scoring.
- The analysis results[10] show that in 5 out of 6 cases, the LWIR camera is the winning alternative (the highest score in each column is the winning one).
- The VIs of hyperspectral cameras are negatively affected by the following drivers: ground pixel size, detector pixels, weight, size and cost. However, an important advantage is spectral resolution.

As shown in several references ([2], [32], [33]), [34]), both spectral bands and camera types are employed in TIR remote sensing. For this reason, further analyses are needed for the case study, in particular, to verify the feasibility of using a hyperspectral camera.

2.4.5 TIR imaging cameras and UAVs on the market

The market offers different TIR camera solutions and UAVs for remote sensing. Since a wide range of thermal infrared imaging cameras is available, Table 2.8[11] focuses on hyperspectral thermal imagers for aerial applications. The table also includes a broadband thermal imager.
Regarding the UAVs, only aircraft capable of carrying a hyperspectral payload are considered. Specifically, three reference UAVs that could be used for the mission are shown in Table 2.9[12]. The presented UAVs are fixed-wing aircraft originally designed for military use [35]. In addition, they can operate at night and in all weather conditions.

Type	Manufacturer	Imager	Spectral range [μm]	Application
HSI (**LWIR**)	Specim	AisaOWL	7.6 - 12.5	Airborne (small aircraft, UAVs)
HSI (**LWIR**)	Itres	TASI-600	8.0 - 11.5	Airborne (aircraft)
HSI (**MWIR**)	Itres	MASI-600	3.0 - 5.0	Airborne (aircraft)
TI (**MWIR**)	Itres	TABI-1800	3.7 - 4.8	Airborne (aircraft)
HSI (**LWIR**)	Telops	Hyper-cam Airborne Mini	7.4 - 11.8	Airborne
HSI (**LWIR**, **MWIR**)	Telops	Hyper-cam Airborne	3.0 - 5.0 8.0 - 12.0	Airborne (aircraft)

Table 2.8. TIR imagers.

Dominator XP (Figure 2.13) is a MALE category UAV [35] for surveillance missions able to carry numerous payloads for military and civil applications [36]. It is a converted

[10] See Attachments.
[11] For more data see: [37], [38], [39], [40], [41], [42], [43], [44], [45].
[12] For more data see: [36], [46], [47], [48], [49], [50], [51], [52].

UAV	Manufacturer	Length [m]	Wing span [m]	MTOW [kg]	Datalink range [km]	Max speed [kts]	Endurance [hrs]	Ceiling [m]	Max payload [kg]	Powerplant
DOMINATOR XP	Aeronautics Defense Systems	8.56	13.5	1900	250 (LOS)	120	> 20	> 5487	373	2 x 170 hp Austro AE300 jet fuel piston engines
FALCO	Leonardo	5.25	7.2	490	200 (LOS)	117	8 - 14	> 5000	70	65 hp gasoline engine
FALCO EVO	Leonardo	6.2	12.5	650	> 200 (LOS)	125	> 20	6000	> 100	80 hp gasoline engine

Table 2.9. UAVs.

Diamond DA-42 Twin-Star, a civil general aviation aircraft, designed to comply with the safety levels of commercial aviation [53]. Consequently, this type of aircraft has accumulated a very high number of flight hours, in the manned configuration, sufficient to certify its operational capabilities and reliability [53].

Figure 2.13. Dominator XP.

FALCO is an MR category UAV [35] that can be equipped with different types of payloads depending on the characteristics of the mission. It is a single-engine aircraft used in surveillance, search and rescue and monitoring scenarios and is designed to fulfil the civil airworthiness requirements prescribed by EASA [54].
Of the three aircraft, FALCO UAVs (Figures 2.14 and 2.15) may be the most suitable for the mission, according to the case study. Compared to the Dominator XP, they have a smaller size and a lower weight. Furthermore, the FALCO UAV was operated in the Piedmont region (Italy) in 2011, thanks to a flight authorisation provided by ENAC, as part of the SMAT-F1 demonstration project relating to a civil monitoring activity in non-segregated airspace and over inhabited territory [54]. Additional information about the SMAT-F1 project can be found in references [55], [56] and [57].

Figure 2.14. FALCO.

Figure 2.15. FALCO EVO.

2.5 Mission and payload definition

The following section addresses flight operational aspects including the mission phases and the concept of operations. Subsequently, a calculation is reported to determine some significant mission-related data.

2.5.1 Mission phases and operations

The simple mission profile defined for the case study is shown in Figure 2.16. It consists of the following nine phases: *taxi-out*, *take-off*, *initial climb*, *climb*, *loiter*, *descent*, *approach*, *landing*, *taxi-in*.
The chosen reference airport is the Turin Airport (ICAO code: LIMF). It is located north-northwest of Turin and represents an ideal solution for the safe execution of the mission, in operational and logistic terms. Since it is an international airport, it has adequate infrastructure and support services even to manage emergencies. Figure 2.17

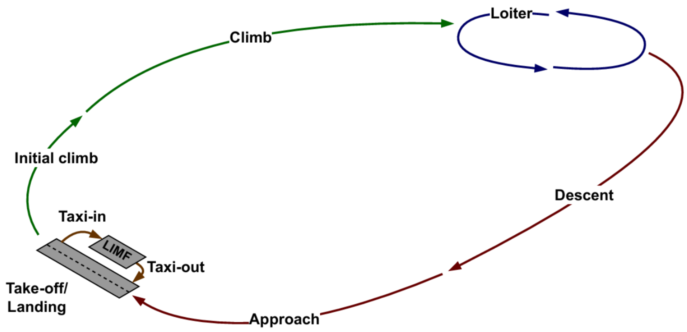

Figure 2.16. Mission profile.

shows the area chosen for the remote sensing operations and the hypothetical flight trajectory, both indicative of how the mission could be carried out. These are represented on a geographical map of the urban area involved, obtained with the ArcGIS Online tool (also used to measure the size of the study area in terms of perimeter and surface) [58]. In particular, the study area covers a rectangular surface of approximately 72 km^2, large enough to include almost the entire city. The figure also shows a schematic representation of the communication link along the trajectory between UAV, GCS and satellites.
As previously specified, the mission must also be performed at night. The main advantage of operating at night is that thermal radiation emitted by objects can be detected more accurately when there are no effects of solar radiation (solar heating) and shadowing [11], allowing better identification of thermal differences or anomalies [13]; however, at night, there is still the contribution of thermal radiation produced by artificial illumination sources. Finally, from a safety point of view, a night flight could be convenient due to air traffic reduction in the airspace.

2.5.2 TIR camera performance and loiter time calculation

A simple MATLAB code[13], based on hyperspectral camera data, is proposed to evaluate the TIR camera performance and image acquisition phase time (i.e., the loiter time). In particular, the code refers to a generic passive payload for EO, not specifically to a hyperspectral camera.
Before introducing the calculation, some assumptions are listed below:

- The code is based on a nadir-pointing[14] camera configuration (i.e., the camera operates perpendicular to the ground) which does not allow obtaining oblique

[13] See Appendix for more information on the calculation and specific terms.
[14] See Figure 2.18.

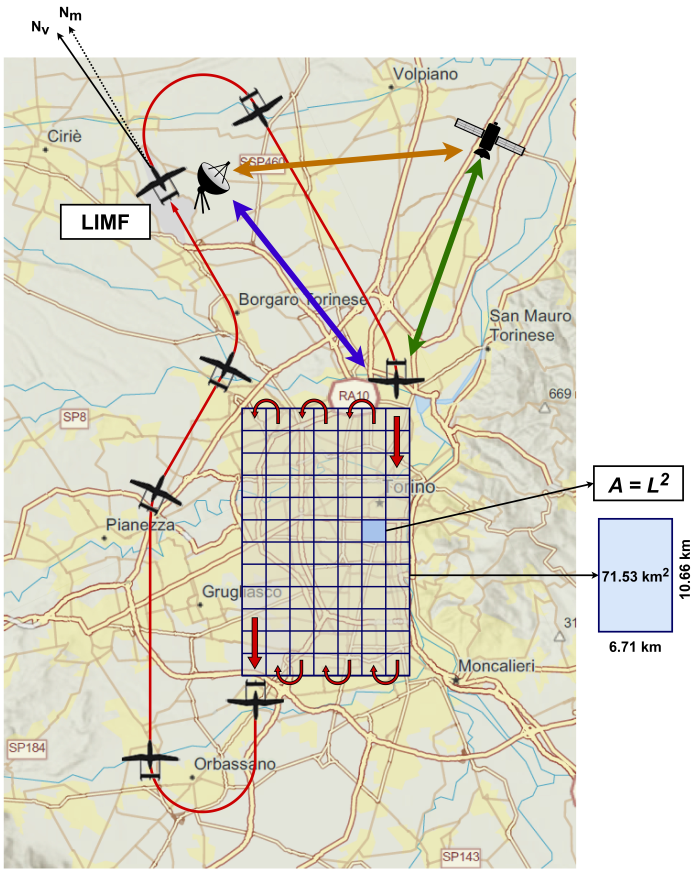

Figure 2.17. Concept of operations.

thermal images. The camera is therefore only able to detect radiation coming from roofs. Furthermore, it would be necessary to cover the study area in multiple directions (north-south, east-west and vice versa) to collect images of all the sides of buildings.

- The ground is assumed to be flat.
- The acquisition of TIR images is assumed to occur frame by frame, while the UAV moves forward. However, when using a hyperspectral payload, it is typical to employ a pushbroom scanning technique. For example, the first three hyperspectral imagers in Table 2.8 are pushbroom systems.

The first part of the code includes the camera characteristics and flight data (airspeed[15] and flight altitude) necessary for the calculation. In particular, the camera characteristics are the following:

[15] It is assumed based on FALCO operational airspeed [54] and considered constant in the code.

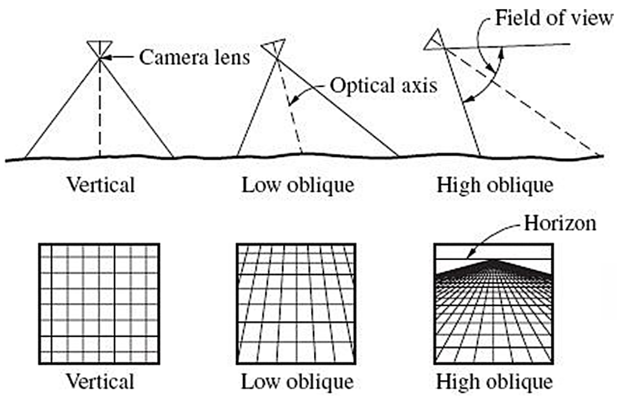

Figure 2.18. Vertical (nadiral) and oblique camera orientation [59].

- *wavelength* used;
- *focal length*;
- *focal ratio* (or *f-number*);
- *lens diameter*;
- *spatial image size* (*detector size*);
- *number of detector pixels.*

The camera specifications used to create the code are mainly assumed from references since the real characteristics of the chosen reference hyperspectral camera (AisaOWL[16]) are not known.

It is important to note that a hyperspectral camera can operate over an extended wavelength range. However, the code is based on a single value, selected to obtain the worst Ground Separation Distance (GSD) in the considered band (LWIR). The number of pixels is defined according to the number of spatial pixels of the reference camera, assuming a square detector instead of a linear array. The remaining defined characteristics are obtained from [60] where some specifications related to hyperspectral objective lenses are reported. In particular, the chosen objective is the OLEL41 (suitable for the LWIR band) which has an f-number similar to that of the AisaOWL camera.

The second part of the code shows the performance calculation of the *spatial resolution* (GSD), the *field of view*, the *swath width*, the *ground area*, the *ground area per pixel* and the *ground pixel size.*

[16] See Table 2.8.

Finally, the loiter time estimation is performed by specifying the covered area dimensions (see Figure 2.17). The idea is to scan the area strip by strip, considering each strip divided (for simplicity) into squares with the side equal to the swath width seen by the camera. Therefore, the camera performs a frame-by-frame image acquisition of each square defined. Moreover, it is possible to determine a single strip area using the swath width and the side of a strip. A side overlap (Figure 2.19[17]) value, the lateral overlap between two strips, is set to ensure complete strip coverage during actual flight operations. Conversely, a front overlap value (overlap in the flight direction) is not

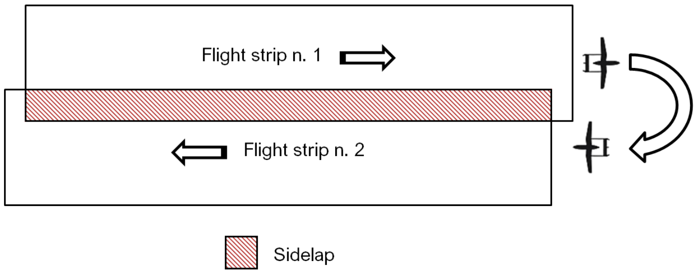

Figure 2.19. Side overlap (or sidelap).

considered. Then, the total number of strips is evaluated. This value is useful for calculating the time required to cover the entire area. Lastly, loiter time is obtained once the time for turns is known. In particular, the time required to complete a re-alignment turn is assumed to be equal to that of a standard turn (360° in 2 minutes). It is important to note that the final time must be compared with the reference UAV endurance to verify that the mission is feasible from this point of view. In this case, the other flight phases are not defined, but the associated times should be much lower than the loiter time.
The following additional observations are reported:

- The number of strips drawn on the map in Figure 2.17 does not correspond to the calculated one (the figure is for illustrative purposes only). In particular, as altitude increases, the number of strips decreases; also, a higher side overlap leads to an increase in the number of strips.
- A more complex calculation should be performed to consider the acquisition of oblique images.
- The calculation could be modified to extend the loiter phase to the urban areas close to the city.

[17] The strips are misaligned in the figure to show the concept of sidelap more clearly.

- Although a specific loitering altitude is not established, the visual flight rules (VFR) and instrument flight rules (IFR), reported in ICAO Annex 2 [61], can be used as a reference to estimate a minimum flight altitude to perform remote sensing operations, considering that the highest obstacle in the study area is the Piedmont Region Skyscraper (209 m). However, the chosen altitude must be consistent with the characteristics of the hyperspectral camera and UAV.

2.5.3 Parametric analysis

Calculations are initially performed using fixed parameters when evaluating a model. Subsequently, a parametric analysis can be conducted to assess how changes in certain input parameters affect the results.

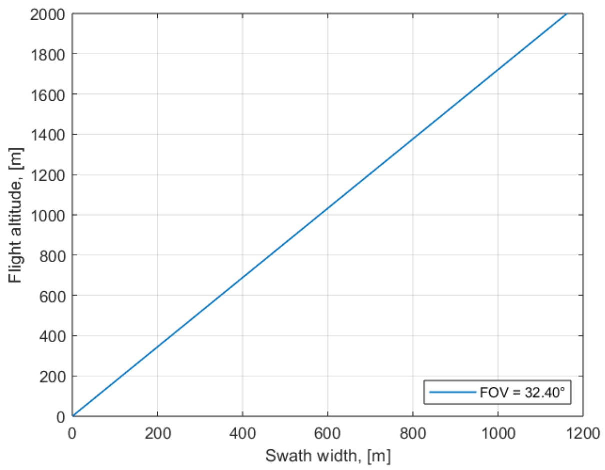

Figure 2.20. Swath width vs. flight altitude (from the code).

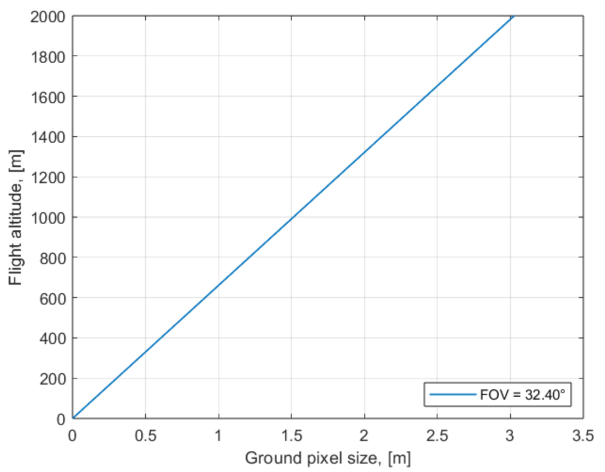

Figure 2.21. Ground pixel size vs. flight altitude (from the code).

The first two graphs (Figures 2.20 and 2.21) illustrate respectively how the swath width and ground pixel size vary with flight altitude, ranging from 0 to 2000 m. Specifically, when comparing the results with those found in the datasheet of the reference camera (Figures 2.22 and 2.23), the resulting trends are similar despite differences in the input data used for the two cameras. It can be seen that the swath width and ground pixel size increase when flying at higher altitudes.

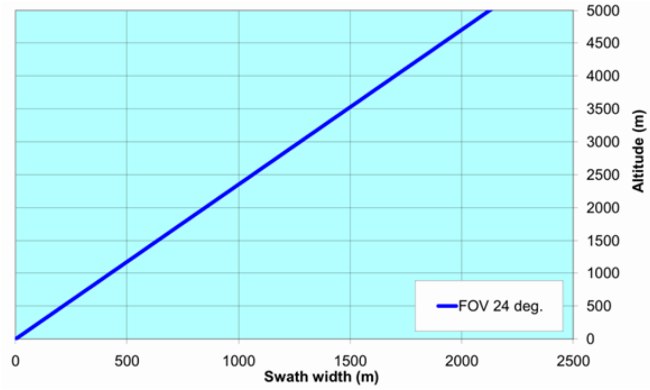

Figure 2.22. Swath width vs. flight altitude (AisaOWL) [37].

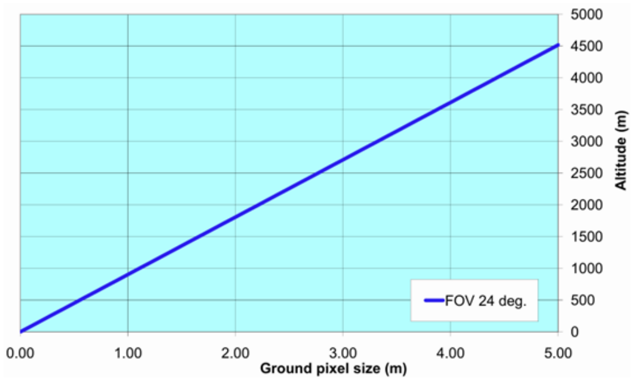

Figure 2.23. Ground pixel size vs. flight altitude (AisaOWL) [37].

In Figure 2.24, different scenarios are analysed by varying the flight altitude, in increments of 100 m from 600 m to 1500 m, and the side overlap value (which ranges from 50% to 90%). The results reveal useful trends for estimating loiter time in various situations. Furthermore, it can be observed that as the side overlap increases, the loiter times tend to rise, while higher altitudes result in shorter loiter times.
Loiter time, ground pixel size and sidelap are then included in a final three-dimensional graph (Figure 2.25). As shown in the figure, the ground pixel size values are a bit high; this result depends on the number of pixels considered (which is low in this case). Therefore, a higher number of pixels would be appropriate.

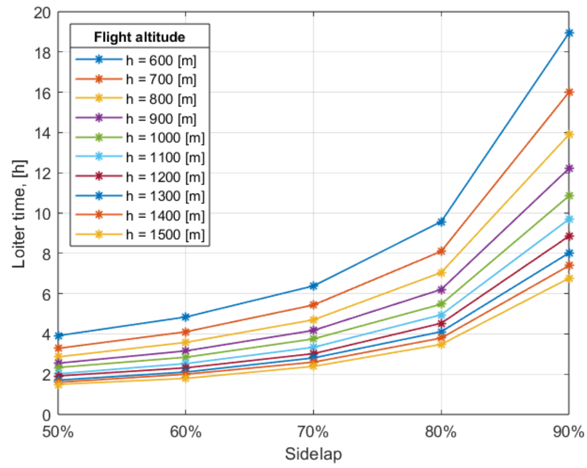

Figure 2.24. Sidelap vs. loiter time for different flight altitudes (from the code).

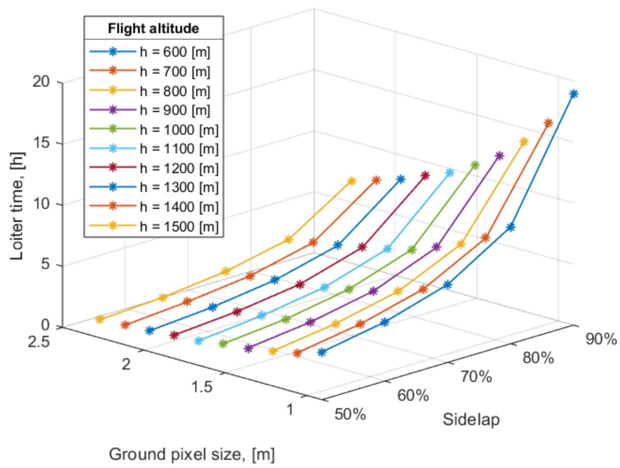

Figure 2.25. 3D plot (from the code).

3 | Preliminary Aircraft Safety Assessment

The following chapter describes the preparatory steps to perform an aircraft-level safety assessment. In particular, two main techniques implemented to study safety during the design and certification phases are presented. The peculiarity of developing a UAV is that additional safety considerations are needed to allow operations in populated urban scenarios. For this reason, remotely piloted aircraft are mainly operated in uninhabited areas. Since the case study is a civil application in an urban environment, a specific reference regulatory documentation developed to assess safety is adopted rather than using a military one, as it usually happens, since larger UAVs, such as those shown in the previous chapter, are typically employed in military or war operations.

3.1 UAS functional analysis

Functional analysis is essential to perform a safety assessment and plays an important role in the various phases of the aircraft design process, especially in the initial ones. In particular, along with the mission definition, this analysis represents an input for conceptual aircraft sizing [5]. Even before designing an aircraft concept, the functions it will have to perform are well known, while the subsystems and components able to execute these functions are not. In this thesis, functional analysis is shown in the safety context, however, it is widely used at the conceptual design level because it allows deriving the functional requirements of a product [5].
Such analysis leads to the identification of functions performed by a product and can be conducted at different levels (system of systems, system, subsystem); depending on the chosen level of detail, the resulting functions can be associated with systems, subsystems and equipment respectively, to subsequently study the existing functional and physical connections [5].
The functional analysis results are the functional tree, the functions/products matrix and the product tree [5]. These outputs are obtained after establishing the level of detail of the analysis. In particular, the functional tree is created first, then the func-

tions/products matrix is defined and finally, the products are grouped to obtain the product tree [5].
A functional tree is a hierarchical diagram in which higher-level functions are broken down into lower-level functions, thus following a top-down approach. As reported in [5], two main rules can be followed to develop this tree: define the functions in the verb-noun form and derive them according to the *how-why* scheme, shown in Figure 3.1. Therefore, to find a lower-level function, it is necessary to understand how the higher-level function can be performed; conversely, proceeding upwards the question to answer is why the function is performed.
A functions/products matrix, on the other hand, allows allocating the functions to the different physical products (parts); the product tree is thus a way to visualise the product divided into its parts (systems, subsystems, equipment), depending on the level of analysis (system of systems, system, subsystem) [5].
Figure 3.2 shows the process followed to perform the functional analysis presented in this thesis. In particular, it includes the UAS and UAV functional trees, the UAV functions/products matrices and the final derived UAV product tree.

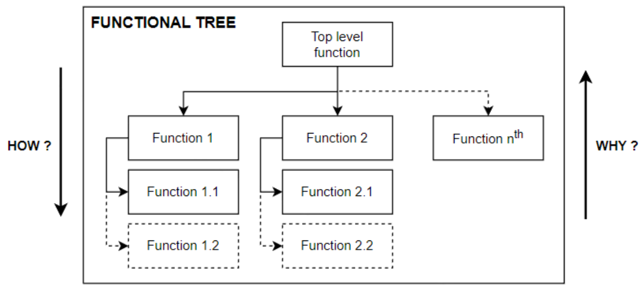

Figure 3.1. *How-why* scheme.

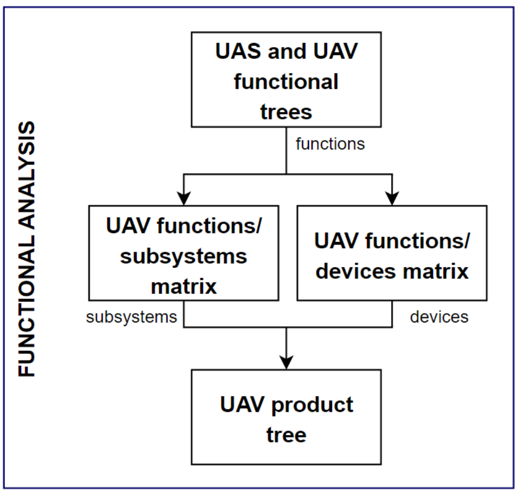

Figure 3.2. Functional analysis process.

3.1.1 UAS functional tree

Figure 3.3 shows the UAS functional tree[1] conceived for the case study.
The term UAS can be defined in different ways. Two reference definitions are given below as examples. The first [62] considers the UAS as:

> *"An aircraft and its associated elements which is operated with no pilot on-board".*

The second one [63] defines it as:

> *"All essential systems for safe flight including the aircraft itself, any external components of the system, such as a ground control station, and the command, control, and communication links between the external components and the aircraft".*

The proposed UAS includes three segments: the *ground segment*, the *communication segment* and the *aerial segment*. Different UAS elements, essential for the mission accomplishment, are assigned to each segment. In particular, the ground segment consists of the airport, the MSC (which remotely supports the role of the GCS), the GCS (which has the primary task of controlling the payload and the UAV) and the radio navigational aids (NAVAIDs). The communication segment includes the ATC, the satellites and eventually a relay station. Lastly, the aerial segment corresponds to the UAV. Specifically, the UAV functions are developed in detail separately. For other elements, only the fundamental functions performed are reported.

3.1.2 UAV functional tree

The UAV functional tree[2] shows the identified functions (Figure 3.4). It consists of fifteen high-level functions further developed into lower-level functions.

3.1.3 UAV functions/subsystems matrix

The functions/subsystems matrix[3] is a means for graphically showing how functions and subsystems are matched. It includes the subsystems that perform the defined functions. i.e., those in the yellow boxes in Figure 3.4. In particular, once the functions are added to the matrix, the subsystems are identified by considering each function individually.

[1] A certain colour indicates a specific level of functions.
[2] A certain colour indicates a specific level of functions.
[3] See Attachments.

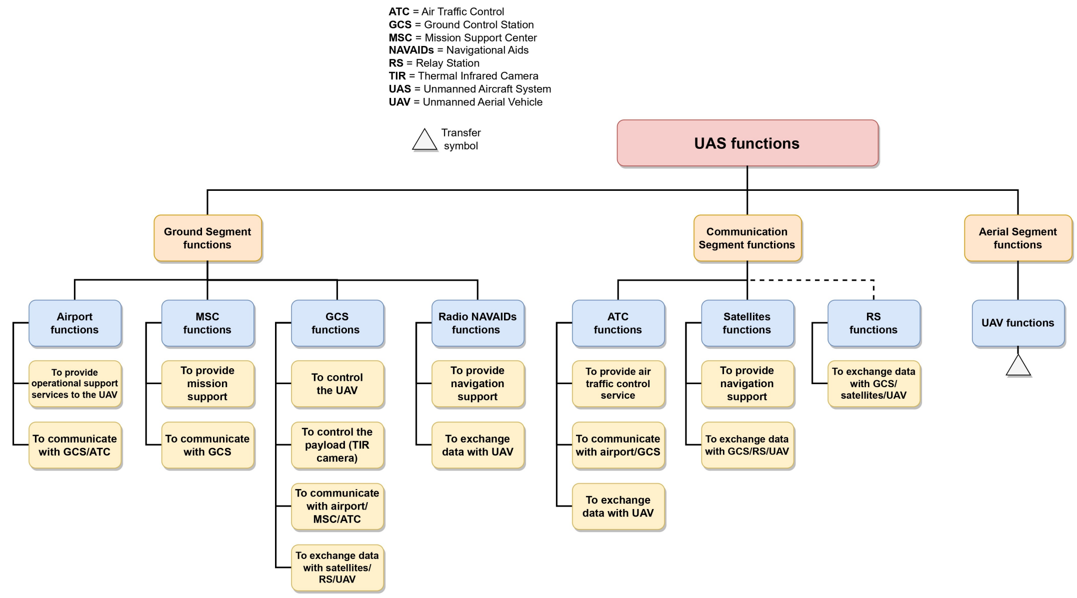

Figure 3.3. UAS functional tree.

3.1.4 UAV functions/devices matrix

The functions/devices matrix[4] is a means for graphically showing how functions and devices are matched. The lower-level functions are associated with the chosen devices using the functions/devices matrix, obtained similarly to the functions/subsystems matrix. In this case, the functions are those written in the green boxes in Figure 3.4.

3.1.5 UAV product tree

The product tree is shown in Figure 3.5. It includes all the subsystems and devices listed in the matrices.

3.2 UAV conceptual design

The conceptual design is the first step in the aircraft design process and constitutes the basis for the subsequent phases (preliminary and detailed). In particular, the initial design choices are important information for a safety assessment.
Since a conceptual design of a reference UAV is not available for this thesis, a simple drawing is proposed in terms of configuration and on-board subsystems (Figure 3.6). A freehand sketch or drawing represents the starting point of a conceptual design; in this way, it is possible to highlight the main features of an aircraft architecture.

[4] See Attachments.

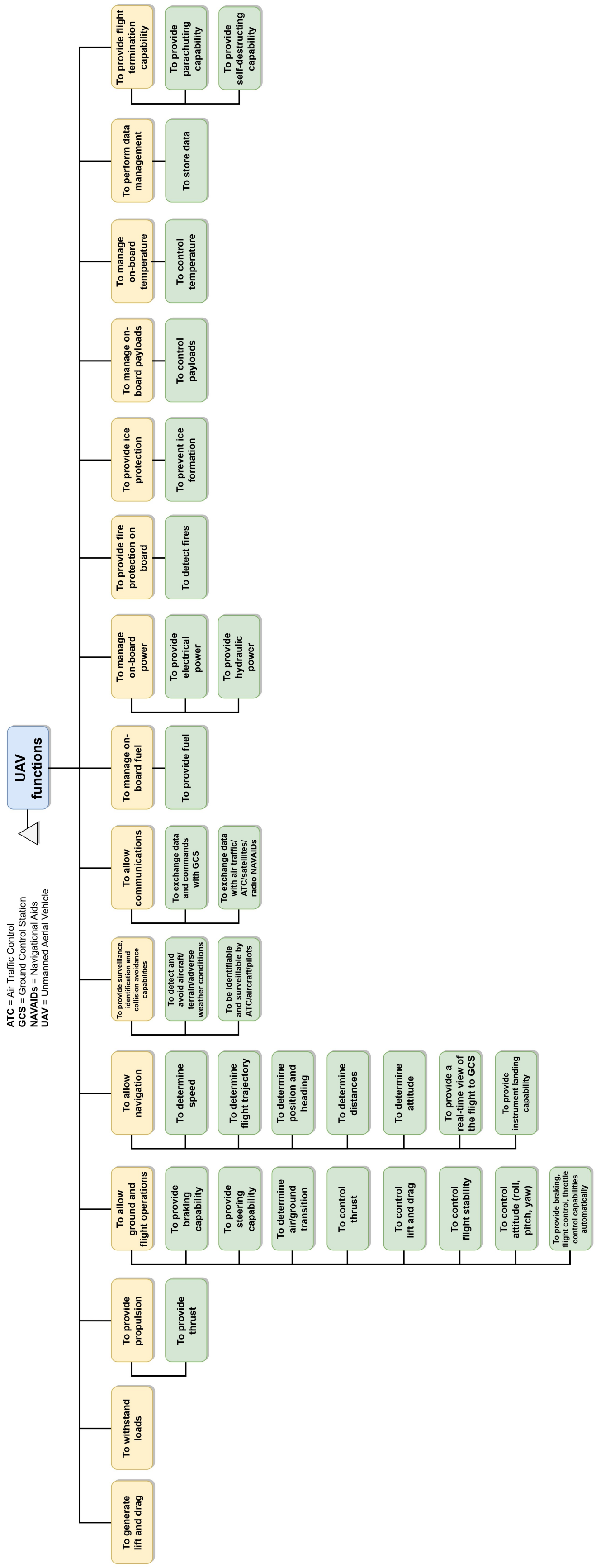

Figure 3.4. UAV functional tree.

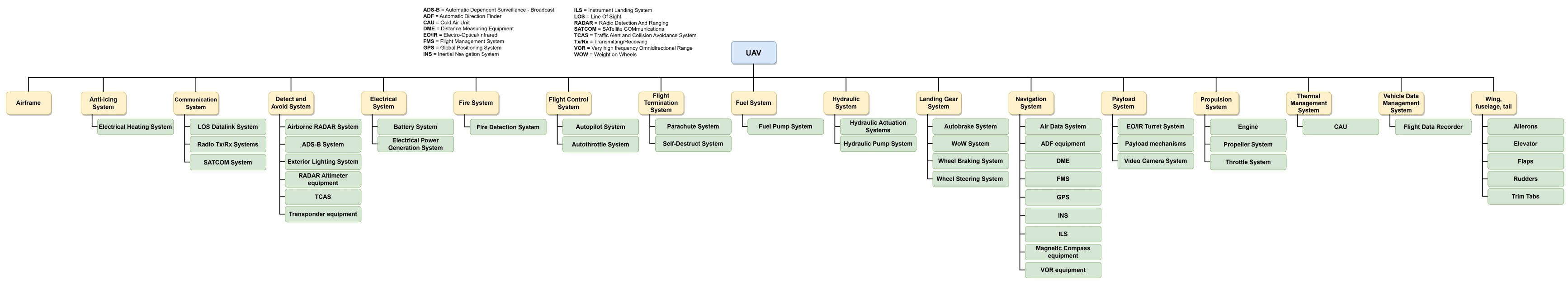

Figure 3.5. UAV product tree.

As can be seen, the defined concept is similar to the FALCO design (Figure 2.14) and is typical of many UAVs. The layout features are the following:

- high-wing;
- rear-mounted engine;
- propeller-driven aircraft;
- boom-mounted tail;
- tricycle landing gear.

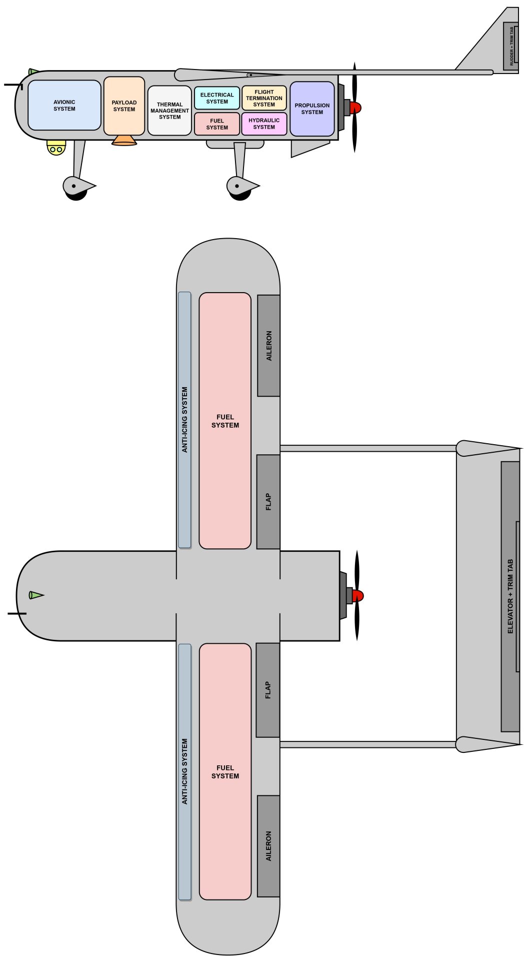

Figure 3.6. UAV concept.

The UAV is assumed to be a fly-by-wire aircraft whose design includes ailerons to control roll, an elevator to control pitch, two rudders to control yaw and flaps to control lift and drag. Furthermore, each rudder and the elevator are equipped with trim tabs. A fixed (non-retractable) landing gear is also considered, with the nose

wheel only steerable, while the two main wheels provide braking capability (but are not steerable).
To conclude, the main UAV subsystems are:

- the *avionic system*;
- the *payload system*;
- the *thermal management system*;
- the *electrical system*;
- the *fuel system*;
- the *hydraulic system*;
- the *propulsion system*;
- the *anti-icing system*;
- the *flight termination system*.

3.3 Introduction to safety

Safety is a key aspect of aviation that influences the airworthiness certification process [64]. In particular, it is associated with the risk management of an aeronautical product that has to be developed [64].
When designing a new aircraft, it is necessary to understand what could go wrong during its operations and what the consequences could be.[5] Specifically, a direct or indirect risk exists when considering the failure of certain functions.
Risk can be seen as an undesirable situation that is likely to occur and potentially has negative effects on the product; instead, safety can be defined as the condition of not having unacceptable risks or the condition in which an acceptable risk level is not exceeded [64]. Risks cannot be completely eliminated or avoided, however, they can be mitigated; for this reason, the idea of acceptable risk is introduced.
In practice, risks are assessed as the product of the severity of the effects and the likelihood of the occurrence [64]. Depending on the category of aircraft considered, the severity categories do not change while the probability values are commensurate with it [64]. The various risks are then included in a risk matrix where the diagonal line

[5] In the case of aircraft, the effects on the aeroplane, crew and passengers are analysed; in contrast, when talking about UAS the focus is on the consequences for the UAV, remote crew and people on the ground or in flight [63].

defines a separation between acceptable and unacceptable ones, as shown in Figure 3.7 where risk is related to failure conditions.

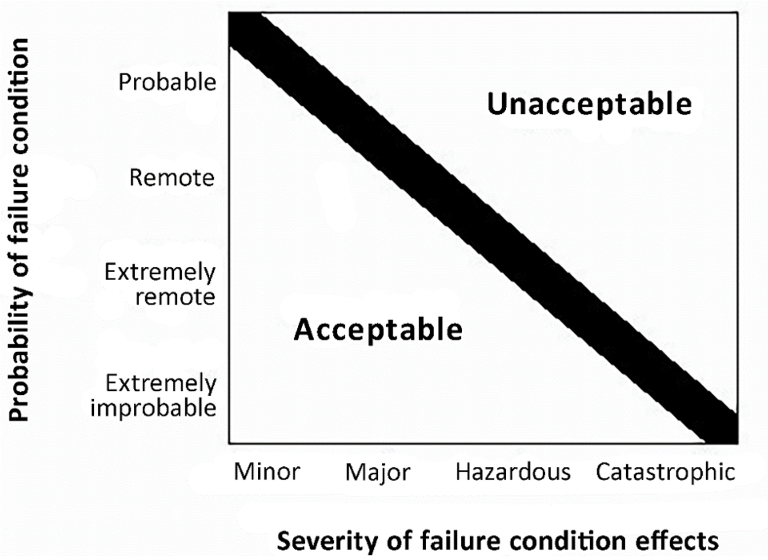

Figure 3.7. Reference matrix for failure conditions [65].

Safety is one of the mandatory requirements, established by airworthiness authorities, for aircraft certification [64]. Specifically, it must be addressed from the earliest stages of the design process; this is also important to avoid higher costs for design changes required to meet the safety objectives [64]. At the beginning of a project, functional safety focuses on identifying the aircraft functions, assessing the risks and establishing how to manage them [64].
Within the regulatory framework of European civil aviation, EASA provides the Certification Specifications (CSs) which include many requirements useful for aircraft development, based on different aircraft categories [64]. In particular, the most important safety requirement is the airworthiness requirement 1309 for on-board systems and equipment. EASA also issues supporting materials called AMCs (Acceptable Means of Compliance) [64].
A safety assessment is needed to demonstrate compliance with the 1309 requirement [64] and is usually conducted based on two well-known guidelines, SAE[6] ARP 4754 and 4761, which are integrated into the aircraft design process. In particular, the safety assessment is carried out through specific safety analyses [64].

[6] SAE is a non-profit organisation focused on advancing mobility technology by providing technical information and standards for aircraft, aerospace vehicles and other self-propelled transportation systems [64].

3.3.1 JARUS AMC RPAS.1309

The following paragraphs briefly introduce the AMC RPAS.1309 proposed by JARUS[7]. This AMC is used in the document as a regulatory reference for assigning the severity of effects and probability of occurrence to failure conditions. A failure condition can be defined as [63]:

> *"A condition having an effect on the UAS, either direct or consequential, which is caused or contributed to by one or more failures or errors considering flight phase and relevant adverse operational or environmental conditions or external events".*

As reported in [62], the AMC is suitable to support the certification process of a civil RPAS and thus comply with requirement 1309. Compliance with the requirement is a necessary step to allow the integration of remotely piloted aircraft into unsegregated airspaces where manned aircraft operate. In particular, this AMC applies to all RPAS categories except autonomous aircraft.
In addition, the document provides a classification of RPAS in terms of increasing complexity level:

(1) *Complexity level I* - An RPAS that has some automatic functions with limited authority on the RPA and limited capability of automatic execution of a mission. Independent manual reversion is always provided. The use of software and Airborne Electronic Hardware (AEH) is limited.

(2) *Complexity level II* - Assigned to any other RPAS not classifiable as Level I. The control systems are likely to have full authority on RPAS flight management and are capable of automatic execution of a mission. In the event of a failure, the pilot can intervene, if required, unless the failure condition can be shown to be extremely improbable. These RPAS are expected to make extensive use of software and AEH.

(3) *Complexity level III* - Assigned to those UAS that are autonomous. This category of UAS is not covered by ICAO and is not covered in this document at the present time.

This classification is required because, as reported in [62], even small RPAS technology can be remarkably sophisticated. Specifically, for an RPAS of complexity level II,

[7] JARUS is a group of experts that provides recommendations and guidance to help integrate unmanned aircraft systems safely into aviation while enabling national authorities to develop their regulations efficiently [66].

the number of potentially catastrophic failure conditions is estimated to be 100 [67], as in the case of a large passenger aircraft belonging to category CS-25. It is worth remembering that failure conditions are classified according to the severity of the effects. The classification proposed in the AMC RPAS.1309 takes into account the following types of failure conditions:

(1) *No safety effect* - Failure conditions that would have no effect on safety. For example, failure conditions that would not affect the operational capability of the RPAS or increase the remote crew workload.

(2) *Minor* - Failure conditions that would not significantly reduce RPAS safety and that involve remote crew actions that are within their capabilities. Minor failure conditions may include a slight reduction in safety margins or functional capabilities, a slight increase in remote crew workload, such as flight plan changes.

(3) *Major* - Failure conditions that would reduce the capability of the RPAS or the ability of the remote crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins, functional capabilities or separation assurance. In addition, the failure condition has a significant increase in remote crew workload or impairs remote crew efficiency.

(4) *Hazardous* - Failure conditions that would reduce the capability of the RPAS or the ability of the remote crew to cope with adverse operating conditions to the extent that there would be the following:

   (i) Loss of the RPA where it can be reasonably expected that a fatality will not occur[8], or

   (ii) A large reduction in safety margins or functional capabilities, or

   (iii) High workload such that the remote crew cannot be relied upon to perform their tasks accurately or completely.

(5) *Catastrophic* - Failure conditions that could result in one or more fatalities.

In addition, the following relationships between the severity of the effects of a failure condition occurring and the associated allowable qualitative probability are established in [67]:

(1) Failure Conditions with *No safety Effect* have *no probability requirement.*

(2) *Minor* Failure Conditions may be *Probable.*

[8] For example, if the RPA only operates over remote areas [62].

(3) *Major* Failure Conditions must be no more frequent than *Remote*.

(4) *Hazardous* Failure Conditions must be no more frequent than *Extremely Remote*.

(5) *Catastrophic* Failure Conditions must be *Extremely Improbable*.

Therefore, an inverse probability-severity relationship is required.
Table 3.1 shows the reference RPAS class and complexity level chosen for the case study, associated with the probability requirements[9] applicable to the failure conditions. The probabilities refer to a CS-23 Class I RPAS (i.e., a single reciprocating engine aircraft with a maximum certified take-off weight under 6000 lbs [68]) of complexity level II [62]. These values are the same for the CS-LUAS class (of equal complexity level) which considers fixed-wing remotely piloted aircraft with a maximum certified take-off weight not exceeding 750 kg [69].

		Classification of Failure Conditions				
		No Safety Effect	Minor	Major	Hazardous	Catastrophic
		Allowable Qualitative Probabilities				
		No Probability Requirement	Probable	Remote	Extremely Remote	Extremely Improbable
Class of RPAS	Complexity Level (CL)	Allowable Quantitative Probabilities (per flight hour)				
RPAS-23 Class I (SRE under 6,000lbs)	II	**No Probability Requirement**	$<10^{-3}$ (1)	$<10^{-5}$ (1)	$<10^{-6}$	$<10^{-7}$ (2)

Table 3.1. Allowable Quantitative Probabilities (per flight hour) [62].

In conclusion, AMC RPAS.1309 suggests as guidance material the SAE ARP 4754 and 4761 recommended practices for conducting a safety assessment. In particular, the methods (techniques) used to perform the safety analyses are explained in the ARP 4761.

3.3.2 Aircraft Functional Hazard Assessment (AFHA)

An AFHA is a method to derive and classify (in terms of risk associated) potential failure conditions (hazards) at the aircraft level [70].
The FHA method can be extended to the system level and is implemented in the early stages of aircraft or system development [71]. According to [70] and [71], the AFHA is divided into the following main steps (Figure 3.8):

(a) Identification of the functions performed by the aircraft (functions are obtained from functional analysis).

(b) Identification of the failure conditions (e.g., loss of functions, malfunctions).

[9] (1) Minor and major failure conditions are usually excluded from a quantitative analysis [62]. (2) At the RPAS functional level, a catastrophic failure condition must not result from any single failure [62].

(c) Identification of associated flight phases.

(d) Determination of consequences of failure conditions.

(e) Classification of failure conditions according to the severity of consequences.

(f) Assignment of probability requirements (safety objectives) to failure conditions.

Regarding point (b), failure conditions can be single or multiple [71]. In addition, they should be considered separately, depending on the mission phase in which they occur, when the effects and severity of consequences change according to the operating conditions [71].

(a) Function	(b) Failure Condition (Hazard Description)	(c) Phase	(d) Effect of Failure Condition	(e) Classification	(f) Probability Requirement	Comments

Figure 3.8. Example of FHA template.

As reported in [63], the classification of some failure conditions may be complex and uncertain since the tendency to be conservative leads to the allocation of severity of consequences and safety objectives higher than necessary. Moreover, the effects of failure conditions depend on the operating and environmental conditions. Thus, these considerations suggest that experience and the ability to capture the actual operating conditions are important skills for conducting a proper hazard assessment.
To conclude, some considerations about the proposed AFHA[10] are listed below:

- Other failure conditions could be identified and studied in addition to those defined.
- When classifying failure conditions in terms of severity of effects, the worst severity is assigned if there is any uncertainty or potential overlap between two severity levels.
- Generally, even if not specified in the assessment, many failure conditions regarding the UAV consequently affect the pilots.
- Take-off and landing are intended as runway manoeuvres; thus, the airborne parts of these phases are included in the initial climb and approach respectively.

[10] See Attachments.

3.3.3 Preliminary Aircraft Fault Tree Analysis (AFTA)

A fault tree analysis is a top-down deductive analysis method, used in the safety assessment process, called preliminary AFTA at the aircraft level [71].
In a fault tree, the causes which lead to a high-level undesired event, called the top event, are investigated. Consequently, the basic events (root causes) can be identified [71]. Considering a preliminary aircraft FTA, the basic events are the top events at the system level. Therefore, to further develop these events, it is necessary to know how the on-board systems are designed.
Boolean logic, represented graphically using logic gates, is applied to explain how lower-level events combine to lead to a top event [71]. In particular, the AND and OR gates (Figure 3.9) are the typical logic gates employed, whose outputs are obtained differently. An AND gate output occurs when all the input events occur; on the other hand, to have an OR gate output it is sufficient that one of the input events occurs.

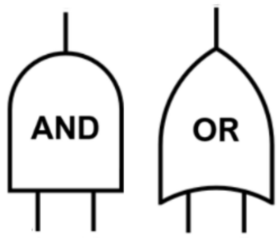

Figure 3.9. AND and OR gates.

To create a fault tree, several graphical symbols can be used [71]. Specifically, three symbols are present in the proposed preliminary UAV fault tree: a triangle, a diamond and a rectangle. A triangle indicates an information transfer, a diamond identifies an undeveloped event (e.g., an event that cannot be further developed due to a lack of information) and a rectangle (box) contains the description of an event (failure condition).
The process of developing a generic fault tree can be summarised in the following steps [71]:

(a) Definition of the top event (undesired event); the top event should state what the event is and when it occurs.

(b) Development of the higher-level events, that cause the top event, through connections with logic gates.

(c) Development of the lower-level events through connections with logic gates.

(d) Expansion of the fault tree with the same logic as long as possible (until root causes are reached depending on the level of detail considered).

The resulting fault tree can be evaluated qualitatively and quantitatively. The qualitative evaluation is carried out by defining the minimal cut set [71]. This procedure simplifies a fault tree by applying boolean logic to determine the smallest combination of basic events that causes the top event [71].
Following this simplification, a quantitative bottom-up evaluation can be performed to calculate the probability of occurrence of the top event and thus verify the compliance with the safety objectives initially imposed [71]. For the calculation, probability values of the lowest-level events must be known [71]. After defining a specific flight time, these values are estimated using chosen failure rates and times of the events [71]. Compared to the entire flight duration, a shorter event time is less safety-critical because the associated risk is lower. This explains the importance of correctly defining the duration of the mission phases and possible modes of operation.
Regarding this thesis, the presented fault tree[11] is developed without evaluating it either qualitatively or quantitatively. As a result, it constitutes a starting point for a complete analysis. The tree is created beginning from the top event (i.e., the loss of the UAV), followed by the immediate events causing it (i.e., the catastrophic and hazardous failure conditions identified in the AFHA). Then, the lower-level events are deduced based on the allocation of functions to devices performed in the functional analysis.
In AMC RPAS.1309, an explicit reference to UAV loss is made only for hazardous failure conditions, while catastrophic ones are defined as conditions that would result in one or more fatalities. However, the loss of the UAV is likely to occur when people are involved in a fatal event (e.g., a crash). Consequently, catastrophic failure conditions are also considered in the tree as potential causes leading to the top event.

[11] See Attachments.

4 | Conclusions

The thesis work illustrated in the previous pages aims to present a comprehensive study of a fixed-wing UAV mission focused on thermal remote sensing of buildings.
A UAV application in an urban scenario could lead to the emergence of new market segments in the coming years. Furthermore, this mission also represents an opportunity to update existing regulations and develop new ones, by testing the safety of such aircraft and their capability to operate in congested airspace above populated areas.
The use of UAVs is a challenge due to their high technological complexity and the risks associated with operations. These aspects must be considered because they affect the economic feasibility and the safe execution of the mission. In particular, the document illustrates how to proceed with the safety assessment of an aircraft at the conceptual design level (e.g., for the development of a new concept).
In the first part of the thesis, the relevance of the proposed case study is highlighted through a stakeholder analysis, which shows how numerous stakeholders may be interested in the mission to achieve multiple objectives. Regarding operational aspects, remote sensing operations are addressed by using a simple calculation to estimate the performance of a thermal camera and the time required for thermal imaging operations of the ground area. In particular, an LWIR sensor for obtaining thermal images under various atmospheric conditions is suggested. In the context of safety assessment, three important outputs are obtained: a functional analysis at the aircraft level, an aircraft functional hazard assessment and a preliminary aircraft fault tree.
The presented study is a valuable reference source for future developments. Further iterations of the proposed process are necessary for an accurate UAV thermal camera selection and to characterise the mission in detail using suitable calculation, modelling and simulation tools. Then, the safety assessment should be revised at the aircraft level and extended to the system level, even introducing quantitative analysis to determine the probability of occurrence of failure conditions and therefore verify the safety objectives.
In conclusion, an estimate of operating costs may be conducted to assess the mission's economic impact, allowing for a comparison with a mission carried out using a manned aircraft.

Appendix

This appendix illustrates the calculation procedure implemented in the code and provides general background information on passive observation payloads.

A.1 Observation payload sizing

A.1.1 Passive observation payloads

Passive observation payloads can collect electromagnetic radiation and process it to obtain useful information about the observed objects (e.g., in the visible and infrared ranges of the electromagnetic spectrum) [10].
A passive payload consists of three fundamental parts [10]:

- a *radiation collector* (e.g., lens or mirror) that captures the radiation emitted or reflected by the observed objects;
- a *detector* that collects the radiation and converts it into an electrical signal;
- *pointing* and *scanning mechanisms* to point and move the payload.

A.1.2 Observation payload requirements

Observation payload requirements can be divided into two major categories: *spatial* and *spectral* [10].
The most important *spatial requirements* are [10]:

- the *spatial resolution*;
- the coverage and size of the observed scene.

  In this case, *swath width* and FOV (*Field Of View*) are the reference parameters. The *swath width* corresponds to the width of the observed area orthogonal to the flight direction, while the FOV is the angle of the scene that the camera can view.

The *spectral requirements* are:

- the number of spectral bands and their allocation;
- the *spectral resolution.*

  Spectral resolution can be seen as the number and size of wavelength intervals of the electromagnetic spectrum to which the payload sensor (detector) is sensible or as the minimum distance between two mean wavelengths that it can separate. Therefore, it is necessary to improve the spectral resolution to obtain a greater number of narrow band intervals.

A.1.3 Camera schematic model

The basic reference model used to create the MATLAB code is shown in Figure A1, where some important characteristics are reported:

- the *focal length* (f), i.e., the distance between the lens and the detector;
- the *flight altitude* (h);
- the *detector size* (D_d) or *image size* (D_i);
- the *scene size* (D_s) or *swath width* (L);
- the *lens diameter* (d_L), considered as the lens aperture diameter;
- the *Field Of View* (FOV).

In addition, the *focal ratio* (or *f-number*) can be defined as [10]:

$$F = \frac{f}{d_L} \tag{a.1}$$

The FOV can be calculated with the following equation:

$$FOV = 2 \cdot \arctan\left(\frac{D_i}{2 \cdot f}\right) \tag{a.2}$$

In conclusion, the *swath width* is defined as:

$$L = 2 \cdot h \cdot \tan\left(\frac{FOV}{2}\right) \tag{a.3}$$

A.1.4 Angular and spatial resolution

Angular and *spatial resolution* are characteristics of an optical payload that indicate its ability to see a scene in detail [10]. In particular, angular resolution (θ) is the minimum angular distance at which two objects can be distinguished. On the other hand, spatial

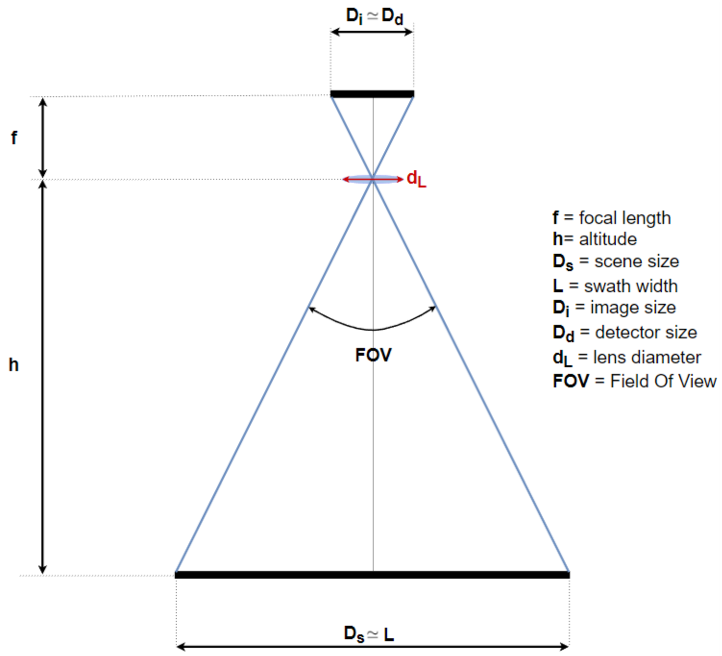

Figure A1. Camera model [10].

(or geometric) resolution defines the minimum distance between two objects at which the sensor can distinguish them.
Figure A2 shows two objects on the ground captured by the sensor on the image plane. They are distant x from each other and R from the camera lens.[1] The θ angle can be defined as the ratio between x and R by considering the small-angle approximation. Applying the Rayleigh criterion, it is possible to calculate θ as [10]:[2]

$$\theta = 1.22 \cdot \frac{\lambda}{d_L} \tag{a.4}$$

Consequently, the formula used to calculate the spatial resolution, called *Ground Separation Distance* (GSD), is the following:

$$GSD = \theta \cdot h \tag{a.5}$$

In conclusion, if the angle formed by two objects close to each other is less than θ or equivalently the distance between the two objects is less than the GSD, these cannot be separated, but are observed as a single object [10].

[1] The range indicated in the figure is equal to the flight altitude.
[2] λ is the wavelength.

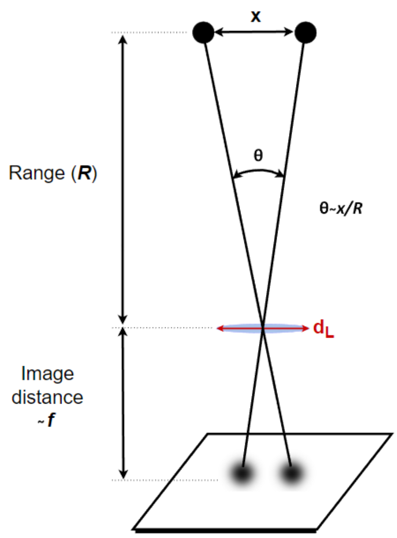

Figure A2. Angular and spatial resolution [10].

A.1.5 Images and ground pixel size

The detector, positioned on the image plane, is an essential component for image acquisition and is generally arranged in arrays [10]. It is typically organised in a matrix format and is made up of a large number of radiation-sensitive elements that detect and convert radiation into electrical signals to obtain images [10].
A pixel is the smallest graphic element corresponding to a radiation-sensitive element and the total number represents a fundamental characteristic of a detector [10]. An image can be arranged as an array or a two-dimensional matrix defined by the number of pixels on rows and columns. In particular, images that cover different bands of the studied electromagnetic spectrum region (e.g., multispectral images) are obtained by overlapping many matrices according to the number of spectral bands [10].
The number of pixels is necessary to evaluate the *ground area per pixel* (A_p), which represents how much area of the scene is contained in a single pixel, and consequently the *ground pixel size* (L_p) [10].
The area seen by the sensor is considered square, for simplicity, as well as the detector, therefore it is equal to:

$$A = L^2 \tag{a.6}$$

The value of A can be divided by the number of total pixels to obtain:[3]

$$A_p = \frac{A}{\#pixels} \tag{a.7}$$

[3] See Figure A3.

Finally, assuming square pixels, the following expression is derived:

$$L_p = \sqrt{A_p} \tag{a.8}$$

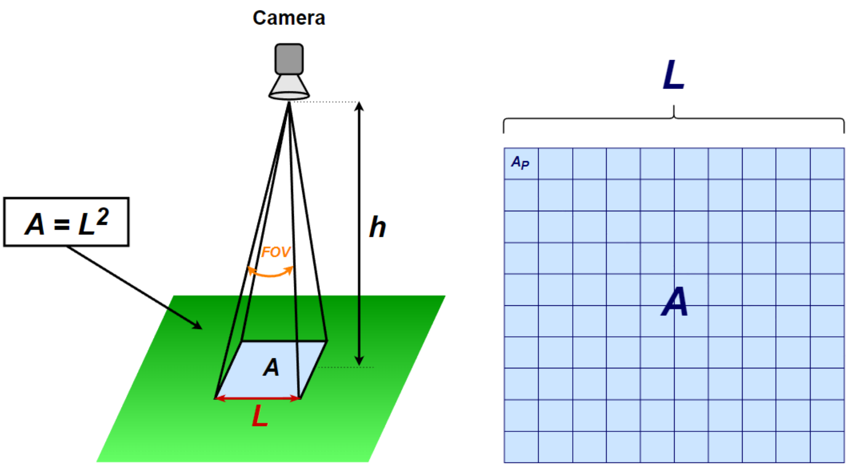

Figure A3. Image acquisition.

A.1.6 MATLAB code

The MATLAB code used is reported below:

```matlab
%%
clear, clc

% Camera characteristics
lambda = 12.5e-6;                    % Wavelength, [m]
f      = 0.0413;                     % Focal length, [m]
F      = 2.5;                        % F-number
d_L    = f/F;                        % Lens diameter, [m]
D_i    = 0.024;                      % Image size (detector size), [m]
pixels = 384^2;                      % Number of pixels

% Flight data
v = 41.152;                          % UAV speed (constant), [m/s] (or 80 [kts])
H = linspace(0,2000,100);            % Flight altitude, [m]

% Camera performance
GSD   = 1.22*lambda*H/d_L;           % Ground Separation Distance, [m]
FOV   = 2*atand(D_i/(2*f));          % Field of View, [deg]
L     = 2*H*tand(FOV/2);             % Swath width, [m]
A     = (L/10^3).^2;                 % Ground area, [km^2]
A_p   = (A*10^6)/pixels;             % Ground area per pixel, [m^2]
L_p   = sqrt(A_p) ;                  % Ground pixel size, [m]

% Figures
figure
plot(L_p,H,LineWidth=1)
legend(sprintf('FOV = %.2f deg',FOV),'Location','southeast')
xlabel('Ground pixel size, [m]')
ylabel('Flight altitude, [m]')
grid on
set(gcf,'color','w');

figure
plot(L,H,LineWidth=1)
legend(sprintf('FOV = %.2f deg',FOV),'Location','southeast')
xlabel('Swath width, [m]')
```

```
ylabel('Flight altitude, [m]')
grid on
set(gcf,'color','w');

%%
clear, clc

% Camera characteristics
lambda = 12.5e-6;                        % Wavelength, [m]
f      = 0.0413;                         % Focal length, [m]
F      = 2.5;                            % F-number
d_L    = f/F;                            % Lens diameter, [m]
D_i    = 0.024;                          % Image size (detector size), [m]
pixels = 384^2;                          % Number of pixels

% Flight data
v = 41.152;                              % UAV speed (constant), [m/s] (or 80 [kts])

i = 1;
time = zeros(10,5);
sl   = zeros(10,5);
L_p  = zeros(10,5);
for h = 600:100:1500                     % Flight altitude, [m]

    % Camera performance
    GSD      = 1.22*lambda*h/d_L;        % Ground Separation Distance, [m]
    FOV      = 2*atand(D_i/(2*f));       % Field of View, [deg]
    L        = 2*h*tand(FOV/2);          % Swath width, [m]
    A        = (L/10^3)^2;               % Ground area, [km^2]
    A_p      = (A*10^6)/pixels;          % Ground area per pixel, [m^2]
    L_p(i,:) = sqrt(A_p);                % Ground pixel size, [m]

    % Loiter time calculation
    l_side   = 10.66e3;                  % Long side, [m]
    s_side   = 6.71e3;                   % Short side, [m]
    A_tot    = l_side*s_side;            % Total area to cover, [m^2]
    A_s      = L*l_side;                 % Single strip area, [m^2]
    A_1      = A_s;                      % First strip area, [m^2]

    j = 1;
    for sidelap = 0.5:0.1:0.9            % Sidelap value
        A_lap   = sidelap*A_s;           % Sidelap area, [m^2]
        A_diff  = A_s-A_lap;             % Difference between single strip area and sidelap area, [m^2]
        strip   = 1;                     % Strip counter
        A_new   = 0;                     % New covered area, [m^2]
        while A_new < A_tot
              A_new = A_diff + A_1;
              strip = strip + 1;
              A_1   = A_new;
        end
        strips    = strip;               % Total number of strips
        t         = (l_side-L)/v/60;     % Time to scan a single strip along the long side, [min]
        tot_t     = strips*t/60;         % Total time to scan all the area to cover, [h]
        turns     = strips*2/60;         % Total time for turns, [h]
        time(i,j) = tot_t+turns;         % Loiter time, [h]
        sl(i,j)   = sidelap;
        A_1 = A_s;
        j = j+1;
    end
        i = i+1;
end

% Figures
figure
for k = 1:10
    plot(sl(k,:),time(k,:), '-*',LineWidth=1)
    hold on
end
lgd = legend('h = 600 [m]','h = 700 [m]','h = 800 [m]','h = 900 [m]','h = 1000 [m]','h = 1100 [m]',...
       'h = 1200 [m]','h = 1300 [m]','h = 1400 [m]','h = 1500 [m]', Location='northwest');
title(lgd, 'Flight altitude');
xticks(0.5:0.1:0.9)
xticklabels(strcat(string(50:10:90), '%'))
xlabel('Sidelap')
ylabel('Loiter time, [h]')
grid on

figure
for k = 1:10
    plot3(sl(k,:),L_p(k,:),time(k,:), '-*',LineWidth=1)
    hold on
```

```
end
lgd = legend('h = 600 [m]','h = 700 [m]','h = 800 [m]','h = 900 [m]','h = 1000 [m]','h = 1100 [m]',...
       'h = 1200 [m]','h = 1300 [m]','h = 1400 [m]','h = 1500 [m]', Location='northwest');
title(lgd, 'Flight altitude');
xticks(0.5:0.1:0.9)
xticklabels(strcat(string(50:10:90), '%'))
xlabel('Sidelap')
ylabel('Ground pixel size, [m]')
zlabel('Loiter time, [h]')
```

A.2 Remote sensing systems and techniques

Remote sensing systems can be divided into two main categories: *framing systems* and *scanning systems* [11]. A framing system captures an instantaneous image (frame) of an area (scene), while a scanning system scans the ground perpendicular to the flight direction to obtain scan lines.

Regarding scanning techniques (Figure A4), two important scanning methods exist: the *pushbroom scanning* (*along-track scanning*) and the *whiskbroom scanning* (*across-track scanning*) [10]. Pushbroom scanning is performed by a scanner that obtains an image by scanning the scene along the track. In this case, a linear array of detectors at the focal plane is used to capture instantaneously an entire single scan line, as wide as the swath width. Therefore, the image (matrix) is assembled line by line as the aircraft moves forward. Whiskbroom scanning, conversely, is performed by a rotating mirror that progressively captures an entire line of the scene along the swath width; thus, the matrix is assembled pixel by pixel.

To conclude, six different types of airborne remote sensing systems for aerial photography, multispectral and hyperspectral imaging are shown in Figure A5.

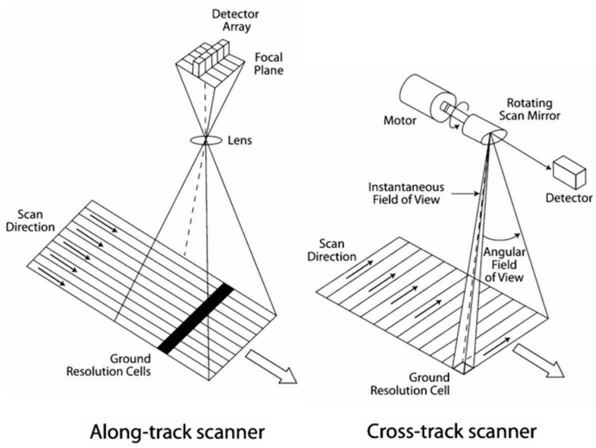

Figure A4. Scanning techniques [11].

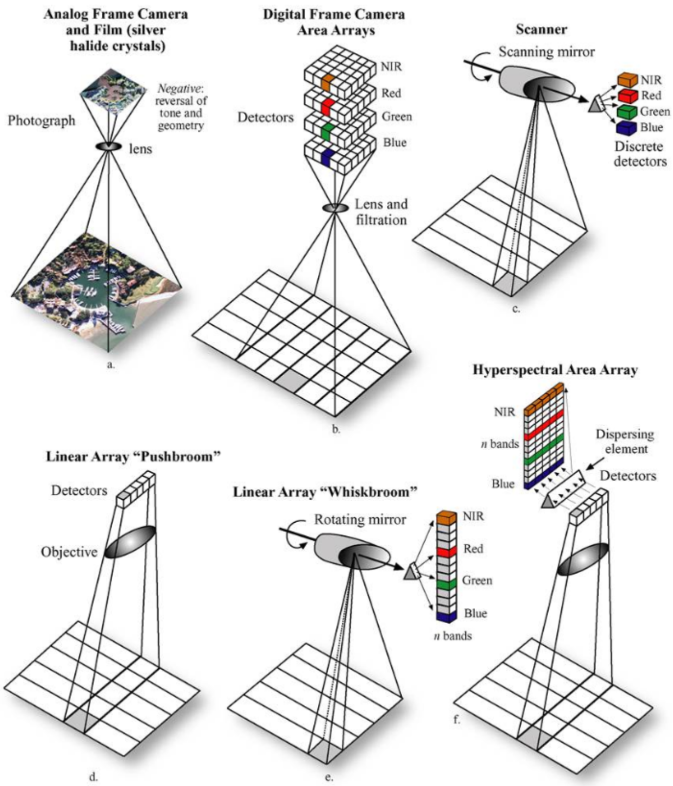

Figure A5. Remote sensing systems [16].

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Attachments

The following documents are included in the next pages:

- STAKEHOLDER ANALYSIS.
- HIGH-LEVEL REQUIREMENTS.
- TIR CAMERA TRADE-OFF ANALYSIS.
- UAV FUNCTIONS/SUBSYSTEMS MATRIX.
- UAV FUNCTIONS/DEVICES MATRIX.
- AIRCRAFT FUNCTIONAL HAZARD ASSESSMENT.
- PRELIMINARY AIRCRAFT FAULT TREE.

Stakeholder analysis

<table>
<tr><th>STAKEHOLDER</th><th>EXAMPLES</th><th>CATEGORY</th><th>OBJECTIVES</th></tr>
<tr><td>UNIVERSITIES</td><td>Politecnico di Torino, Università di Torino</td><td rowspan="3">END USER</td><td rowspan="3">• To obtain thermal data of buildings for future studies on energy efficiency and decarbonisation.
• To gather trends in heat dispersion (heat loss) and energy consumption.
• To create new urban digital twins and update existing ones.
• To spectrally characterize building materials using the spectral thermal signature.
• To study heat island effect.
• To contribute to scientific publications and knowledge progress in different fields.
• To collaborate with industry on sustainable energy solutions.
• To share results with the public and raise awareness of the topic.
• To drive innovation in energy-efficient technologies.
• To fill the gap between research and practical applications.
• To support climate initiatives and agreements.
• To test new airborne cameras and technologies.</td></tr>
<tr><td>SCIENTIFIC COMMUNITY</td><td>-</td></tr>
<tr><td>RESEARCH CENTERS</td><td>Fondazione LINKS, Eurac Research</td></tr>
<tr><td rowspan="2">GOVERNMENTS</td><td rowspan="2">EU, Regione Piemonte, Città di Torino</td><td>SPONSOR</td><td>• To enhance people’s health and quality of life.
• To enhance city sustainability.
• To increase public awareness of air pollution and CO_2 issues.
• To promote innovation in energy efficiency.
• To be a forerunner for future projects.
• To pursue green goals.
• To reduce harmful emissions.
• To improve public image and credibility.
• To improve the local economy.</td></tr>
<tr><td>CUSTOMER</td><td>• To obtain data for urban planning, decarbonisation and energy efficiency strategies.
• To identify energy consumption of critical facilities for energy efficiency renovations.
• To identify urban heat islands and heat losses.
• To develop environmental policies and regulations.
• To support research on local climate change.
• To update the energy classification of buildings.</td></tr>
<tr><td>ENVIRONMENTAL ORGANISATIONS</td><td>-</td><td>END USER</td><td>• To use data for environmental advocacy and awareness campaigns.
• To promote sustainable practices.</td></tr>
</table>

INDUSTRIES/ENTERPRISES	-	**CUSTOMER**	• To reduce carbon-related pollution according to energy efficiency and air quality standards. • To prove to the authorities the effectiveness of the green policies and standards introduced. • To reduce heating costs of infrastructures and buildings. • To sell next-generation photovoltaic panels and heat pumps.
		SPONSOR	• To identify energy consumption of critical facilities for energy efficiency renovations. • To identify areas for investment in renewable energy sources and new business. • To develop renewable energy technologies.
ENERGY COMPANIES	-	**CUSTOMER**	• To propose new energy contracts and plans for customers. • To sell next-generation photovoltaic panels and heat pumps. • To propose energy efficiency measures to customers.
INHABITANTS	-	**END USER**	• To have benefits from energy efficiency renovations of buildings. • To identify critical areas for air pollution and consequently the health risks. • To know about energy-saving and cost-saving practices and technologies. • To enhance the quality of life. • To reduce pollutant and CO_2 emissions. • To lower energy bills.
MISSION DEVELOPERS	LEONARDO	**DEVELOPER**	• To study new operational scenario configurations and applications. • To collect useful data about the UAS for different purposes. • To contribute to the mission accomplishment and success. • To study the feasibility of re-using the UAV in other contexts. • To study the integration of the UAV within a non-segregated and controlled airspace for operational and safety goals. • To verify compliance with regulations and safety standards.
UAS MANUFACTURER/OWNER	LEONARDO	**SUPPLIER**	• To start a new profitable business. • To test existing/new technologies, prototypes and payloads. • To collect useful data about the UAS for different purposes. • To showcase capabilities to customers and competitors. • To improve UAS performance. • To contribute to the mission accomplishment and success. • To study the feasibility of re-using the UAV in other contexts. • To verify compliance with regulations and safety standards.

MISSION OPERATORS	LEONARDO, ENAV	**OPERATOR**	• To provide accurate and high-quality images. • To contribute to the mission accomplishment and success. • To study the integration of the UAV within a non-segregated and controlled airspace for operational and safety goals. • To study the feasibility of re-using the UAV in other contexts. • To verify compliance with regulations and safety standards. • To show the UAS operability within the mission scenario. • To explore the potential of aerial thermal remote sensing at city-scale.
URBAN PLANNERS, ARCHITECTS, DESIGNERS	-	**END USER**	• To benefit from reliable data for developing urban design strategies. • To identify areas for urban regeneration and green spaces. • To develop plans against climate change. • To design energy-efficient solutions for reducing environmental impact and carbon footprint.
ENGINEERS	-	**END USER**	• To design renewable energy technologies. • To develop new materials and construction methods for energy efficiency. • To plan energy retrofit interventions.
ENVIRONMENTAL POLICY-MAKERS	-	**END USER**	• To develop long-term targeted policies and programs for reducing energy consumption and emissions. • To update existing energy policies based on available data. • To define energy retrofit policies.

High-level requirements

ID	HIGH-LEVEL REQUIREMENTS
MIS-01	The mission shall be carried out using a fixed-wing UAV.
MIS-02	The mission shall be performed to acquire thermal images through aerial remote sensing, by detecting TIR radiation from buildings in an urban scenario.
MIS-03	The mission shall be accomplished in the coming years to meet the 2030 goal of carbon neutrality.
MIS-04	The mission shall prove that its implementation in operational contexts like the case study is feasible.
MIS-05	The mission shall prove that the integration of a fixed-wing UAV within a non-segregated and controlled airspace is feasible.
MIS-06	The mission shall prove that the use of a fixed-wing UAV is cost-effective.
MIS-07	The mission shall be carried out considering the possibility of introducing COTS components to reduce costs.
MIS-08	The mission shall be designed according to the size of the defined study area.
CON-01	The fixed-wing UAV shall be equipped with a thermal infrared (TIR) camera.
CON-02	The fixed-wing UAV shall be equipped with a digital camera that works simultaneously with the TIR camera, to obtain images in the visible light spectrum along the covered area.
FUN-01	The fixed-wing UAV shall store thermal images on board.
FUN-02	The fixed-wing UAV shall perform a stable flight to get accurate thermal images.
FUN-03	The fixed-wing UAV shall be able to accurately follow the chosen flight path to capture thermal images with precision above the designated area.
FUN-04	The fixed-wing UAV shall be able to fly automatically.
FUN-05	The fixed-wing UAV shall be able to “detect and avoid” air traffic.
FUN-06	The fixed-wing UAV shall be able to terminate the flight if required, by parachuting/self-destructing or implementing emergency flight procedures.
FUN-07	The fixed-wing UAV shall be able to fly in different weather conditions to perform thermal remote sensing in any situation.
FUN-08	The on-board TIR camera shall be able to capture high-resolution thermal images of the urban scenario in atmospheric conditions such as rain, fog, mist, haze and snow.
FUN-09	The on-board TIR camera shall perform nadiral and oblique thermal imaging of buildings.
DES-01	The fixed-wing UAV shall have performance and endurance characteristics suitable for carrying out the mission.
DES-02	The fixed-wing UAV shall have flight, navigation and communication capabilities like those of manned aircraft.
DES-03	The on-board cameras shall be stabilised during the flight.

DES-04	EASA regulations shall be applied to the project.
SAF-01	The UAS shall comply with safety regulations, standards and guidelines to operate safely.
SAF-02	Emergency procedures shall be established for the safety of air traffic and people on the ground.
SAF-03	JARUS AMC RPAS.1309, SAE ARP4754 and SAE ARP4761 shall be implemented in the project to perform a safety assessment.
OPE-01	The UAS shall include the aerial segment, the ground segment and the communication segment.
OPE-02	The fixed-wing UAV shall be operated remotely by a pilot-in-command.
OPE-03	The fixed-wing UAV shall be operated according to air law.
OPE-04	The fixed-wing UAV shall be operated above the study area at an altitude that complies with the flight rules and the performance of the TIR camera.
OPE-05	The fixed-wing UAV shall be operated to acquire a wide range of thermal images both day and night.
OPE-06	The fixed-wing UAV shall be operated at different times of the year.
ENV-01	The on-board TIR camera shall be able to function according to the temperature at the operating altitude.
PHY-01	The on-board TIR camera shall be compatible with the fixed-wing UAV in terms of weight and size to be installed on it.

TIR camera trade-off analysis

Does the driver on the column influence the driver on the row?

FOMs	DRIVERS	Ground pixel size	Spectral resolution/ #spectral bands (channels)	Detector pixels (#pixels)	Atmospheric conditions	Operating Temperature	Camera weight	Camera size	Camera cost	Rank	Rank % (WF)	WF 1	WF 2	WF 3	WF 4	WF 5	MWIR camera	LWIR camera	Hyperspectral MWIR camera	Hyperspectral LWIR camera
		Performance			*Environment*		*Physical characteristics*		*Cost*		**WEIGHT FACTORS**						**SCORES**			
Performance	Ground pixel size		0	1	0	0	0	0	0	3	0,14	0,25	0,50	0,17	0,17	0,17	9	9	7	7
	Spectral resolution/ #spectral bands (channels)	0		1	0	0	0	0	0								1	1	9	9
	Detector pixels (#pixels)	1	0		0	0	0	0	0								9	9	7	7
Environment	Atmospheric conditions	0	0	0		0	0	0	0	0	0,00	0,25	0,17	0,50	0,17	0,17	7	8	7	8
	Operating temperature	0	0	0	0		0	0	0								9	9	8	8
Physical characteristics	Camera weight	1	1	1	1	1		1	0	12	0,55	0,25	0,17	0,17	0,50	0,17	1	1	2	2
	Camera size	1	1	1	1	1	1		0								1	1	2	2
Cost	Camera cost	1	1	1	1	1	1	1		7	0,32	0,25	0,17	0,17	0,17	0,50	2	2	3	3
										22	1,00	1,00	1,00	1,00	1,00	1,00				

VALUE INDICES							
	MWIR camera	1,5	8,8	18,3	16,8	4,4	4,4
	LWIR camera	1,5	9,0	18,5	17,5	4,5	4,5
	Hyperspectral MWIR camera	1,0	5,4	12,0	9,7	2,5	2,9
	Hyperspectral LWIR camera	1,0	5,6	12,1	10,1	2,6	3,0

UAV functions/subsystems matrix

Subsystems \ Functions	To generate lift and drag	To withstand loads	To provide propulsion	To allow ground and flight operations	To allow navigation	To provide surveillance, identification and collision avoidance capabilities	To allow communications	To manage on-board fuel	To manage on-board power	To provide fire protection on board	To provide ice protection	To manage on-board payloads	To manage on-board temperature	To perform data management	To provide flight termination capability
Airframe		■								■					
Anti-icing System											■				
Communication System							■								
Detect and Avoid System						■									
Electrical System									■						
Fire System										■					
Flight Control System				■											
Flight Termination System															■
Fuel System								■							
Hydraulic System									■						
Landing Gear System		■		■											
Navigation System					■										
Payload System					■							■			
Propulsion System			■	■											
Thermal Management System													■		
Vehicle Data Management System														■	
Wing, Fuselage, Tail	■			■											

UAV functions/devices matrix

Devices \ Functions	To provide thrust	To provide braking capability	To provide steering capability	To determine air/ground transition	To control thrust	To control lift and drag	To control flight stability	To control attitude (roll, pitch, yaw)	To provide braking, flight control, throttle control capabilities automatically	To determine speed	To determine flight trajectory	To determine position and heading	To determine distances	To determine attitude	To provide a real-time view of the flight to GCS	To provide instrument landing capability	To detect and avoid aircraft/terrain/adverse weather conditions	To be identifiable and surveillable by ATC/aircraft/pilots	To exchange data and commands with GCS	To exchange data with air traffic/ATC satellites/radio NAVAIDs	To provide fuel	To provide electrical power	To provide hydraulic power	To detect fires	To prevent ice formation	To control payloads	To control temperature	To store data	To provide parachuting capability	To provide self-destructing capability
Ailerons								X																						
Airborne RADAR System																	X													
Air Data System										X			X																	
Autobrake System									X																					
Automatic Dependent Surveillance - Broadcast (ADS-B) System																	X													
Automatic Direction Finder (ADF) equipment												X																		
Autopilot System									X																					
Autothrottle System									X																					
Battery System																						X								
Cold Air Unit (CAU)																											X			
Distance Measuring Equipment (DME)													X																	
Electrical Heating System																									X					
Electrical Power Generation System																						X								
Electro-Optical/Infrared (EO/IR) Turret System															X															
Elevator								X																						
Engine	X																													
Exterior Lighting System																		X												
Fire Detection System																								X						
Flaps						X																								
Flight Data Recorder																												X		
Flight Management System (FMS)											X																			
Fuel Pump System																					X									
Global Positioning System (GPS)										X		X	X																	
Hydraulic Actuation Systems																							X							
Hydraulic Pump System																							X							
Inertial Navigation System (INS)										X		X		X																
Instrument Landing System (ILS)																X														
Line Of Sight (LOS) Datalink System																			X											
Magnetic Compass equipment												X																		
Parachute System																													X	
Payload mechanisms																										X				
Propeller System	X																													
RADAR Altimeter equipment													X				X													
Radio Transmitting/Receiving (Tx/Rx) Systems																				X										
Rudders								X																						
SATCOM System																			X											
Self-Destruct System																														X
Throttle System					X																									
Traffic Alert and Collision Avoidance System (TCAS)																	X													
Transponder equipment																		X												
Trim Tabs							X																							
VHF Omnidirectional Range (VOR) equipment												X																		
Video Camera System															X															
Weight on Wheels (WoW) System				X																										
Wheel Braking System		X	X																											
Wheel Steering System			X																											

Aircraft Functional Hazard Assessment

Phase
Taxi
Take-off
Initial Climb
Climb
Loiter
Descent
Approach
Landing

Classification	Probability Requirement (pfh)
No safety effect	No probability requirement
Minor	< 1.0E-3
Major	< 1.0E-5
Hazardous	< 1.0E-6
Catastrophic	< 1.0E-7

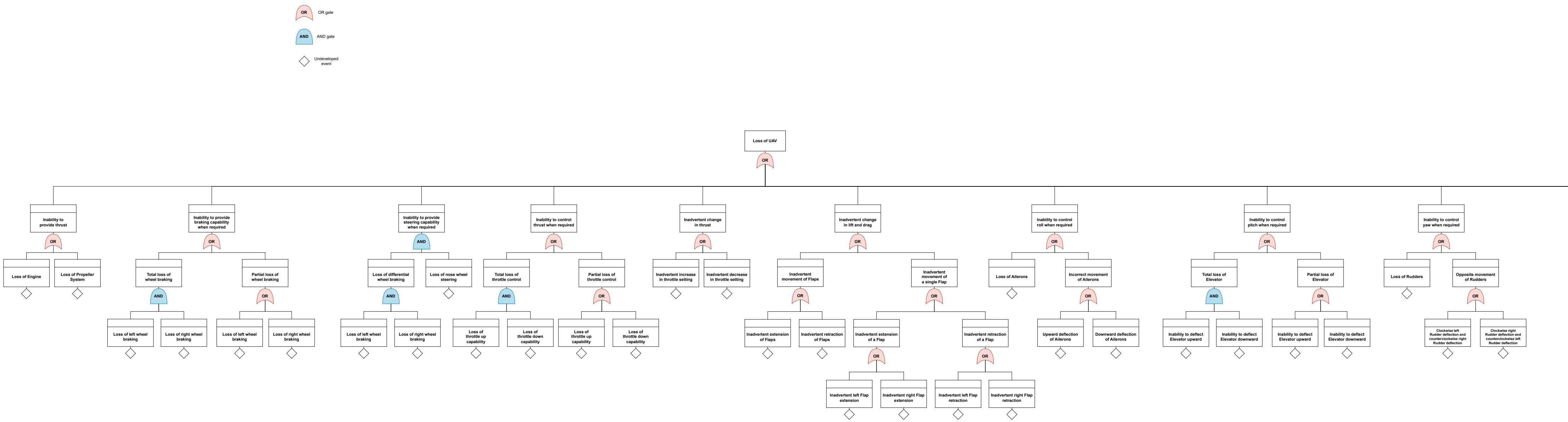
Function	Failure Condition (Hazard Description)	Phase	Effect of Failure Condition	Classification	Probability Requirement	Comments
To provide thrust	Inability to provide thrust	Taxi	The UAV is unable to move on the ground, therefore the mission cannot be carried out.	No safety effect	No probability requirement	
	Inability to provide thrust	Take-off	The UAV cannot complete the take-off roll, therefore the mission is aborted.	Major	< 1.0E-5	
	Inability to provide thrust	Initial Climb, Climb, Loiter, Descent, Approach	The UAV is unable to sustain itself in flight, therefore it loses altitude. This condition can lead to the loss of the UAV and human lives.	Catastrophic	< 1.0E-7	
To provide braking capability	Inability to provide braking capability when required	Taxi	The UAV is unable to decelerate and stop. This condition could lead to a collision with aircraft, buildings and objects on the manoeuvring area and aprons. People could also be involved in a fatal accident.	Catastrophic	< 1.0E-7	Taxiing operations are performed at low speeds, therefore a collision should not result in the loss of the UAV.
	Inability to provide braking capability when required	Take-off	The UAV is unable to decelerate on the runway in the event of an aborted take-off. This condition can lead to a runway overrun. As a result, the loss of the UAV is possible.	Hazardous	< 1.0E-6	During take-off operations, there should be no people, vehicles and aircraft on the runway and at the end of the runway.
	Inability to provide braking capability when required	Landing	The UAV is unable to decelerate on the runway, thus, a runway overrun can occur. As a result, the loss of the UAV is possible.	Hazardous	< 1.0E-6	During landing operations, there should be no people, vehicles and aircraft on the runway and at the end of the runway.
	Inadvertent braking capability provided at low speed	Taxi	The UAV is unable to taxi maintaining a certain speed because it decelerates.	No safety effect	No probability requirement	
	Inadvertent braking capability provided at high speed	Take-off	The UAV decelerates, therefore the take-off roll cannot be completed.	Major	< 1.0E-5	
	Inability to provide differential braking capability when required	Taxi	The UAV is unable to perform tight changes of direction.	Minor	< 1.0E-3	Differential braking capability is provided only in specific cases where steering is not sufficient to steer the UAV (e.g., to park the UAV).
	Inadvertent differential braking capability provided at low speed	Taxi	This failure condition affects the movements on the manoeuvring area. The UAV tends to deviate slightly from the taxiway.	No safety effect	No probability requirement	
	Inadvertent differential braking capability provided at high speed	Take-off, Landing	The UAV decelerates and does not maintain the runway centerline. The take-off roll cannot be completed. In addition, the occurrence of the failure condition could affect the ground controllability of the UAV.	Major	< 1.0E-5	
To provide steering capability	Inability to provide steering capability when required	Taxi	The UAV cannot change direction to avoid potential aircraft, buildings, objects, people on the manoeuvring area and aprons. A collision could occur and cause one or more fatalities if pilots are unable to stop the UAV.	Catastrophic	< 1.0E-7	Taxiing operations are performed at low speeds, therefore a collision should not result in the loss of the UAV.
	Inability to provide steering capability when required	Take-off, Landing	The UAV cannot follow the runway centerline if a correction is necessary. A runway excursion could occur (if pilots are unable to stop the UAV), involving nearby aircraft and people in an accident, in which the UAV could suffer irreparable damage.	Catastrophic	< 1.0E-7	
	Inadvertent steering capability provided at low speed	Taxi	This failure condition affects the movements on the manoeuvring area. The UAV tends to deviate slightly from the taxiway.	No safety effect	No probability requirement	
	Inadvertent steering capability provided at high speed	Take-off, Landing	The UAV does not maintain the runway centerline. The take-off roll cannot be completed. In addition, the occurrence of the failure condition could affect the ground controllability of the UAV.	Major	< 1.0E-5	
	Incorrect steering capability provided	Taxi	The turning radius of the UAV on the ground could be too large or too small.	Minor	< 1.0E-3	
To determine air/ground transition	Inability to determine air/ground transition when required	Take-off, Landing	The UAV cannot establish whether it is still on the ground or airborne and vice versa. It is not possible to establish whether and when to brake and/or steer the UAV during landing. Different UAV subsystems can be affected by a lack of information during take-off and landing operations.	Major	< 1.0E-5	
	Incorrect air/ground transition determined	Take-off, Landing	The UAV cannot establish properly whether it is still on the ground or airborne and vice versa. It is not possible to establish whether and when to brake and/or steer the UAV during landing. Different UAV subsystems can be affected by incorrect information during take-off and landing operations.	Major	< 1.0E-5	
To control thrust	Inability to control thrust when required	Taxi	The UAV is unable to accelerate or decelerate. The mission cannot be carried out. This condition could lead to a collision with aircraft, buildings and objects on the manoeuvring area and aprons. People could also be involved in a fatal accident.	Catastrophic	< 1.0E-7	Taxiing operations are performed at low speeds, therefore a collision should not result in the loss of the UAV.
	Inability to control thrust when required	Take-off	The UAV cannot begin the take-off roll. As a result, take-off is aborted.	No safety effect	No probability requirement	
	Inability to control thrust when required	Take-off	The UAV is unable to slow down (decelerate) in the event of an aborted take-off. As a result, a runway overrun can occur with the consequent loss of the UAV.	Hazardous	< 1.0E-6	During take-off operations, there should be no people, vehicles and aircraft on the runway and at the end of the runway.
	Inability to control thrust when required	Initial Climb, Climb, Loiter, Descent, Approach	Speed and altitude control are compromised. This condition could lead to the loss of the UAV and human lives in the event that an emergency landing cannot be performed.	Catastrophic	< 1.0E-7	This failure condition is particularly critical if it occurs during flight phases close to the ground (e.g., it could not be possible to reduce thrust during landing flare or increase thrust for a go-around).
	Inadvertent change in thrust	Taxi	This failure condition affects the movements on the manoeuvring area because the UAV accelerates or decelerates unintentionally.	No safety effect	No probability requirement	
	Inadvertent change in thrust	Take-off	Take-off is rejected if there is an unintentional deceleration of the UAV caused by a decrease in thrust.	Major	< 1.0E-5	
	Inadvertent change in thrust	Landing	The UAV tends to accelerate unintentionally if there is an increase in thrust during the deceleration/braking phase (landing roll).	Major	< 1.0E-5	
	Inadvertent change in thrust	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition can affect manoeuvres and flight operations (e.g., attitude corrections could be required). For example, during turns and low-speed manoeuvres, a change in thrust could lead to loss of control of the UAV due to stalling. This situation can lead to the loss of the UAV in a fatal accident.	Catastrophic	< 1.0E-7	
To control lift and drag	Inability to control lift when required	Take-off	The UAV is unable to control lift when an increase is needed, therefore it requires a longer take-off roll.	No safety effect	No probability requirement	From a strictly operational point of view, it is assumed that the runway is long enough to perform a take-off in a clean configuration.
	Inability to control lift when required	Initial Climb, Climb	The UAV is unable to control lift when an increase is needed, therefore it is forced to climb more slowly. It could be necessary to change the climb attitude.	Minor	< 1.0E-3	
	Inability to control drag when required	Descent, Approach	The UAV is unable to control drag when an increase is needed, therefore it is forced to descent faster. It could be necessary to change the descent attitude. The resulting landing speed could be too high and therefore a longer landing roll could be necessary.	Minor	< 1.0E-3	From a strictly operational point of view, it is assumed that the runway is long enough to perform a landing in a clean configuration.
	Inadvertent change in lift and drag	Take-off	The take-off configuration of the UAV changes and this leads to a rejected take-off.	Major	< 1.0E-5	A change in lift and drag could also be asymmetric.

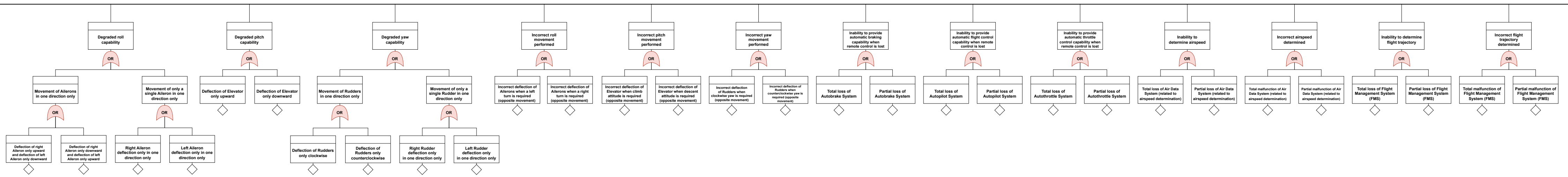
	Inadvertent change in drag	Landing	The UAV experiences less deceleration on the runway if there is an unintentional decrease in drag.	No safety effect	No probability requirement	
	Inadvertent change in lift and drag	Initial Climb, Climb, Loiter, Descent, Approach	This condition causes a change in flight attitude. The UAV could stall, especially during low-speed manoeuvres and turns. The resulting risk is losing control of the UAV which could crash and cause a fatal accident.	Catastrophic	< 1.0E-7	A change in lift and drag could also be asymmetric and cause an asymmetric stall.
To control flight stability	Inability to control flight stability when required	Initial Climb, Climb, Loiter, Descent, Approach	The UAV is not trimmable on the longitudinal and/or vertical axis. It is difficult to carry out the mission in these conditions, therefore it is aborted.	Minor	< 1.0E-3	It is assumed that the UAV is always statically stable, therefore no shifts in the center of gravity are necessary.
To control attitude (roll, pitch, yaw)	Inability to control roll, pitch, yaw when required	Taxi	The UAV fails pre-flight checks, therefore the mission is aborted.	No safety effect	No probability requirement	
	Inability to control roll when required	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot perform turns to change trajectory or heading. In addition, it is unable to make corrections around the roll axis (e.g., correct yaw-induced roll). It cannot perform manoeuvres to avoid a possible mid-air collision, which can result in the loss of the UAV and a fatal accident.	Catastrophic	< 1.0E-7	
	Inability to control pitch when required	Take-off	The UAV is unable to pitch at rotation speed (V_R), therefore take-off is aborted. A runway overrun could occur if the take-off run cannot be stopped (e.g., the runway is not long enough). As a result, the loss of the UAV is possible.	Hazardous	< 1.0E-6	During take-off operations, there should be no people, vehicles and aircraft on the runway and at the end of the runway.
	Inability to control pitch when required	Initial Climb, Climb, Loiter, Descent, Approach	It is not possible to control the attitude (e.g., the UAV could be unable to maintain a certain attitude, avoid stalling due to low speeds and perform the landing flare). In addition, the failure condition does not allow changes in altitude, therefore the UAV risks an impact with the ground. In general, the UAV could also be unable to manoeuvre to avoid a possible mid-air collision. In conclusion, the loss of the UAV and a fatal accident cannot be ruled out as a consequence of this failure condition.	Catastrophic	< 1.0E-7	
	Inability to control yaw when required	Initial Climb, Climb, Loiter, Descent, Approach	The UAV is unable to correct the drift angle (caused by the wind), the left-turning tendencies and skidding/slipping (e.g., during turns). Therefore, especially during a turn, the UAV could stall or spin. The resulting loss of control can cause the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	
	Inadvertent roll movement performed	Initial Climb, Climb, Loiter, Descent, Approach	The UAV changes flight trajectory and heading. Therefore, the flight orientation changes.	Minor	< 1.0E-3	
	Inadvertent pitch movement performed	Initial Climb, Climb, Loiter, Descent, Approach	The UAV changes attitude and airspeed. Therefore, the flight orientation changes.	Minor	< 1.0E-3	
	Inadvertent yaw movement performed	Initial Climb, Climb, Loiter, Descent, Approach	The UAV orientation changes, therefore flight operations are affected.	Minor	< 1.0E-3	
	Degraded roll capability	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can roll, but the performance is reduced (e.g., the roll movement is performed with a certain latency).	Major	< 1.0E-5	
	Degraded roll capability	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can only turn in one direction, therefore manoeuvrability and navigation capability are affected. The UAV must travel longer distances to follow the desired trajectory (this leads to an increase in flight times and fuel consumption). In addition, a mid-air collision could not be avoided due to reduced manoeuvrability. In conclusion, this condition could lead to the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	
	Degraded pitch capability	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can pitch, but the performance is reduced (e.g., the pitch movement is performed with a certain latency).	Major	< 1.0E-5	
	Degraded pitch capability	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can only pitch in one direction, therefore manoeuvrability and navigation capability are affected. In addition, a mid-air collision could not be avoided due to reduced manoeuvrability. The UAV could impact the ground due to loss of control after take-off and before landing. In conclusion, this failure condition could lead to the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	
	Degraded yaw capability	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can yaw, but the performance is reduced (e.g., the yaw movement is performed with a certain latency).	Major	< 1.0E-5	
	Degraded yaw capability	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can only yaw in one direction, therefore manoeuvrability and navigation capability are affected. The UAV is unable to properly correct the drift angle, the left-turning tendencies and skidding/slipping. Therefore, especially during a turn, the UAV could stall or spin. The resulting loss of control can cause the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	
	Incorrect roll movement performed	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes the UAV to turn excessively or insufficiently, therefore a certain flight trajectory/heading is difficult to follow.	Major	< 1.0E-5	
	Incorrect roll movement performed	Initial Climb, Climb, Loiter, Descent, Approach	The UAV turns in the opposite direction to the intended one. This condition affects the controllability of the UAV (a loss of control can occur), therefore it is especially risky at low altitude and in automatic flight conditions if the pilots are unable to intervene. In conclusion, a potentially catastrophic collision leading to the loss of the UAV cannot be ruled out.	Catastrophic	< 1.0E-7	
	Incorrect pitch movement performed	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes the UAV to pitch excessively or insufficiently, therefore a certain airspeed/attitude is difficult to reach.	Major	< 1.0E-5	
	Incorrect pitch movement performed	Initial Climb, Climb, Loiter, Descent, Approach	The UAV pitches in the opposite direction to the intended one. This condition affects the controllability of the UAV (a loss of control can occur) and could lead it to stall, therefore it is especially risky at low altitude and in automatic flight conditions if the pilots are unable to intervene. In conclusion, a potentially catastrophic collision leading to the loss of the UAV cannot be ruled out.	Catastrophic	< 1.0E-7	
	Incorrect yaw movement performed	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes the UAV to yaw excessively or insufficiently.	Major	< 1.0E-5	
	Incorrect yaw movement performed	Initial Climb, Climb, Loiter, Descent, Approach	The UAV yaws in the opposite direction to the intended one, therefore the controllability is affected (a loss of control can occur). The UAV cannot properly correct the drift angle, the left-turning tendencies and skidding/slipping. Therefore, especially during a turn, it could stall or spin. The resulting loss of control can cause the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	
To provide braking, flight control, throttle control capabilities automatically	Inability to provide automatic braking capability when remote control is lost	Take-off, Landing	The UAV cannot automatically slow down and stop during a landing or a rejected take-off. Since pilots cannot intervene, a runway overrun could occur resulting in the loss of the UAV.	Hazardous	< 1.0E-6	During take-off and landing operations, there should be no people, vehicles and aircraft on the runway and at the end of the runway.
	Inability to provide automatic braking capability when remote control is possible	Take-off, Landing	The UAV cannot automatically slow down and stop during a landing or a rejected take-off, but pilots can intervene to manage the situation.	Minor	< 1.0E-3	
	Inability to provide automatic flight control capability when remote control is lost	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot perform manoeuvres automatically. Since pilots cannot intervene, the UAV can be lost in an accident fatally involving people.	Catastrophic	< 1.0E-7	
	Inability to provide automatic flight control capability when remote control is possible	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot perform manoeuvres automatically, but pilots can intervene to manage the situation.	Major	< 1.0E-5	
	Inability to provide automatic throttle control capability when remote control is lost	Initial Climb, Climb, Loiter, Descent, Approach	The UAV is unable to manage the thrust automatically. Since pilots cannot intervene, the UAV can be lost in an accident fatally involving people.	Catastrophic	< 1.0E-7	
	Inability to provide automatic throttle control capability when remote control is possible	Initial Climb, Climb, Loiter, Descent, Approach	The UAV is unable to manage the thrust automatically, but pilots can intervene to manage the situation.	Major	< 1.0E-5	
To determine speed	Inability to determine airspeed	Taxi	The UAV cannot safely perform ground movements, because pilots cannot adjust braking and thrust without a speed indication. For this reason, the mission is interrupted.	Minor	< 1.0E-3	
	Incorrect airspeed determined	Taxi	The UAV cannot safely perform ground movements, because pilots cannot adjust braking and thrust without a proper speed indication. For this reason, the mission is interrupted.	Minor	< 1.0E-3	
	Inability to determine airspeed	Take-off	Take-off is rejected according to operating procedures. Pilots cannot establish if the UAV is accelerating and if rotation speed (V_R) is reached.	Major	< 1.0E-5	
	Incorrect airspeed determined	Take-off	Take-off is rejected according to operating procedures. Pilots cannot establish properly if the UAV is accelerating and if rotation speed (V_R) is reached.	Major	< 1.0E-5	
	Inability to determine airspeed	Initial Climb, Climb, Loiter, Descent, Approach	Navigation and remote sensing operations are affected. In particular, aerial imaging cannot be performed without an airspeed value. In addition, useful information is missing to perform manoeuvres and control of speed. The UAV, in automatic flight or controlled remotely by the pilots, cannot establish if it is flying too slow (close to stall speed) or too fast (overspeed). In the first situation, it could stall and the possible loss of control can lead to the loss of the UAV in a collision with the ground. People can also be involved in a fatal accident.	Catastrophic	< 1.0E-7	
	Incorrect airspeed determined	Initial Climb, Climb, Loiter, Descent, Approach	Navigation and remote sensing operations are affected. In particular, aerial imaging cannot be performed without a proper airspeed value. In addition, accurate information is missing to perform manoeuvres and control of speed. The UAV, in automatic flight or controlled remotely by the pilots, cannot properly establish if it is flying too slow (close to stall speed) or too fast (overspeed). In the first situation, it could stall and the possible loss of control can lead to the loss of the UAV in a collision with the ground. People can also be involved in a fatal accident.	Catastrophic	< 1.0E-7	
	Inability to determine vertical speed	Initial Climb, Climb, Descent, Approach	It is not possible to climb and descend at the desired rates, therefore the UAV cannot fly according to operating procedures.	Minor	< 1.0E-3	
	Incorrect vertical airspeed determined	Initial Climb, Climb, Descent, Approach	It is not possible to climb and descend at the desired rates, therefore the UAV cannot fly according to operating procedures.	Minor	< 1.0E-3	
	Inability to determine ground speed	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition affects flight navigation and UAV trajectory planning because ground speed information is important for evaluating wind speed and estimating flight times and fuel consumption.	Major	< 1.0E-5	

	Incorrect ground speed determined	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition affects flight navigation and UAV trajectory planning because ground speed information is important for evaluating wind speed and estimating flight times and fuel consumption.	Major	< 1.0E-5	
To determine flight trajectory	Inability to determine flight trajectory	Initial Climb, Climb, Loiter, Descent, Approach	The ability of the UAV to navigate between waypoints or radio NAVAIDs and to perform airborne remote sensing operations are affected. If the UAV is in automatic flight and the pilots cannot control it, it can deviate from the chosen flight trajectory and follow a random one. This condition can lead to the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	This failure condition is a problem especially in the case of automatic flight operations, if the pilots are unable to intervene.
	Incorrect flight trajectory determined	Initial Climb, Climb, Loiter, Descent, Approach	The ability to navigate between waypoints or radio NAVAIDs and to perform airborne remote sensing operations are affected. If the UAV is in automatic flight and the pilots cannot control it, it can deviate from the chosen flight trajectory and follow an incorrect one. This condition can lead to the loss of the UAV in an accident fatally involving people.	Catastrophic	< 1.0E-7	This failure condition is a problem especially in the case of automatic flight operations, if the pilots are unable to intervene.
To determine position and heading	Inability to determine position	Initial Climb, Climb, Loiter, Descent, Approach	The navigation capability is reduced because the UAV is unable to establish where it is. Consequently, it cannot follow the flight plan or define another flight path to continue the mission or return to the airport. Remote sensing operations cannot be carried out because a position indication is required. Loss of the UAV and a possible catastrophic accident cannot be ruled out.	Catastrophic	< 1.0E-7	This failure condition is a problem especially in the case of automatic flight operations, if the pilots are unable to intervene.
	Incorrect position determined	Initial Climb, Climb, Loiter, Descent, Approach	The navigation capability is reduced because the UAV is unable to properly establish where it is. Consequently, it cannot follow the flight plan or define another flight path to continue the mission or return to the airport. Remote sensing operations cannot be carried out because an accurate position indication is required. Loss of the UAV and a possible catastrophic accident cannot be ruled out.	Catastrophic	< 1.0E-7	This failure condition is a problem especially in the case of automatic flight operations, if the pilots are unable to intervene.
	Inability to determine heading	Initial Climb, Climb, Loiter, Descent, Approach	The navigation capability is reduced because the UAV is unable to establish the direction of flight. Consequently, it cannot follow the flight plan or define another flight path to continue the mission or return to the airport. Remote sensing operations cannot be carried out because a heading value is required. Loss of the UAV and a possible catastrophic accident cannot be ruled out.	Catastrophic	< 1.0E-7	This failure condition is a problem especially in the case of automatic flight operations, if the pilots are unable to intervene.
	Incorrect heading determined	Initial Climb, Climb, Loiter, Descent, Approach	The navigation capability is reduced because the UAV is unable to properly establish the direction of flight. Consequently, it cannot follow the flight plan or define another flight path to continue the mission or return to the airport. Remote sensing operations cannot be carried out because an accurate heading value is required. Loss of the UAV and a possible catastrophic accident cannot be ruled out.	Catastrophic	< 1.0E-7	This failure condition is a problem especially in the case of automatic flight operations, if the pilots are unable to intervene.
To determine distances	Inability to determine vertical distance (altitude and distance from the ground)	Initial Climb, Climb, Loiter, Descent, Approach	Remote sensing cannot be carried out because, from an operational point of view, aerial images must be obtained at a specific altitude. In addition, the lack of an indication of altitude/distance from the ground increases the risk of collision of the UAV with the ground or buildings. Therefore, a catastrophic accident and the loss of the UAV cannot be ruled out.	Catastrophic	< 1.0E-7	This failure condition could be particularly critical in mountainous or hilly areas and in certain situations (e.g., automatic flight), especially if the pilots are unable to intervene.
	Incorrect vertical distance determined (altitude and distance from the ground)	Initial Climb, Climb, Loiter, Descent, Approach	Remote sensing cannot be carried out because, from an operational point of view, aerial images must be obtained at a specific altitude. In addition, an incorrect indication of altitude/distance from the ground increases the risk of collision of the UAV with the ground or buildings. Therefore, a catastrophic accident and the loss of the UAV cannot be ruled out.	Catastrophic	< 1.0E-7	This failure condition could be particularly critical in mountainous or hilly areas and in certain situations (e.g., automatic flight), especially if the pilots are unable to intervene.
	Inability to determine slant range	Initial Climb, Climb, Loiter, Descent, Approach	The navigation capability is reduced because the UAV is unable to establish the distance that separates it from a radio beacon (radio NAVAID).	Minor	< 1.0E-3	
	Incorrect slant range determined	Initial Climb, Climb, Loiter, Descent, Approach	The navigation capability is reduced because the UAV is unable to properly establish the distance that separates it from a radio beacon (radio NAVAID).	Minor	< 1.0E-3	
To determine attitude	Inability to determine attitude	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes a reduction in navigation, stability and control capabilities of the UAV. The lack of attitude data affects the use of the payload to obtain aerial imagery and the ability to perform manoeuvres. Therefore, the UAV could stall or spin following a manoeuvre. This situation could lead to the loss of the UAV and human lives, as a result of the impact with the ground.	Catastrophic	< 1.0E-7	This failure condition could be particularly critical in certain situations (e.g. automatic flight), especially if the pilots are unable to intervene.
	Incorrect attitude determined	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes a reduction in navigation, stability and control capabilities of the UAV. Incorrect attitude data affects the use of the payload to obtain aerial imagery and the ability to perform manoeuvres properly. Therefore, the UAV could stall or spin following a manoeuvre. This situation could lead to the loss of the UAV and human lives, as a result of the impact with the ground.	Catastrophic	< 1.0E-7	This failure condition could be particularly critical in certain situations (e.g. automatic flight), especially if the pilots are unable to intervene.
To provide a real-time view of the flight to GCS	Inability to provide a real-time view of the flight to GCS	Taxi	The mission is aborted because the pilots do not have a view of the external environment, therefore they would not be able to avoid a possible collision of the UAV on the manoeuvring area.	Major	< 1.0E-5	
	Inability to provide a real-time view of the flight to GCS	Take-off, Landing	Pilots would not be able to follow the runway centerline. In the case of take-off, the take-off roll is rejected. In general, a runway excursion could occur if the pilots are unable to stop the UAV, involving nearby aircraft and people in an accident in which the UAV could suffer irreparable damage.	Catastrophic	< 1.0E-7	
	Inability to provide a real-time view of the flight to GCS	Initial Climb, Climb, Loiter, Descent, Approach	The mission can only be continued under instrument flight rules (IFR) or in automatic flight. Pilots cannot visually determine the separation from the ground and the position of the UAV. The failure condition causes a significant reduction in safety margins and affects situational awareness (e.g., the ability to prevent a possible mid-air collision is reduced).	Major	< 1.0E-5	
To provide instrument landing capability	Inability to provide instrument landing capability when remote control is lost	Approach	The UAV is unable to follow the ideal descent path, in terms of lateral and vertical guidance, to reach the runway safely. This condition can lead to the loss of the UAV in a collision with the ground or buildings. People can also be involved in a fatal accident.	Catastrophic	< 1.0E-7	
	Inability to provide instrument landing capability when remote control is possible	Approach	The UAV is unable to follow the ideal descent path in terms of lateral and vertical guidance, to reach the runway safely, but pilots can intervene to manage the situation.	Major	< 1.0E-5	
To detect and avoid aircraft/terrain/adverse weather conditions	Inability to detect and avoid aircraft	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes a large reduction in safety margins and separation assurance.	Hazardous	< 1.0E-6	According to JARUS AMC RPAS.1309, this failure condition is classified as hazardous.
	Inability to detect and avoid an aircraft on a conflicting trajectory that fails to separate	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition leads to the loss of the UAV and fatalities in a mid-air collision.	Catastrophic	< 1.0E-7	According to JARUS AMC RPAS.1309, this failure condition is classified as catastrophic.
	Incorrect detection and avoidance of nearby aircraft	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition reduces the separation assurance and can lead the pilots or the UAV to perform incorrect manoeuvres, increasing the possibility of a mid-air collision resulting in the loss of the UAV and fatalities.	Catastrophic	< 1.0E-7	
	Incorrect detection and avoidance of nearby aircraft (false alarm)	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes the pilots or the UAV to perform unnecessary manoeuvres (there is no risk of collision with another aircraft). However, the manoeuvres could increase the risk of conflict with aircraft in the surrounding airspace due to a reduction in separation assurance.	Major	< 1.0E-5	
	Inability to detect and avoid terrain	Initial Climb, Climb, Loiter, Descent, Approach	A crash into the ground resulting in the loss of the UAV can occur. People could also be involved in a fatal accident.	Catastrophic	< 1.0E-7	
	Incorrect detection and avoidance of terrain	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes the pilots or the UAV to perform incorrect manoeuvres that could lead to the loss of the UAV as a result of an impact with the ground. People could also be involved in a fatal accident.	Catastrophic	< 1.0E-7	
	Incorrect detection and avoidance of terrain (false alarm)	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition causes the pilots or the UAV to perform unnecessary manoeuvres (there is no risk of impact with the ground). However, the manoeuvres could increase the risk of conflict with aircraft in the surrounding airspace due to a reduction in separation assurance.	Major	< 1.0E-5	
	Inability to detect and avoid adverse weather conditions	Initial Climb, Climb, Loiter, Descent, Approach	The UAV can be exposed to dangerous weather conditions (e.i. phenomena associated with thunderstorms such as severe turbulence, hail, icing and microbursts). Damages and loss of control of the UAV can occur. As a consequence, the loss of the UAV in a ground impact involving people in a fatal accident cannot be ruled out.	Catastrophic	< 1.0E-7	
To be identifiable and surveillable by ATC/aircraft/pilots	Inability to be identifiable and surveillable by ATC	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot be accurately tracked because ATC does not receive the necessary information. This condition causes a reduction in the separation assurance from other aircraft.	Major	< 1.0E-5	
	Inability to be identifiable and surveillable by aircraft	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot be tracked by aircraft. This condition causes a reduction in the separation assurance and could lead to the loss of the UAV and fatalities in a mid-air collision with another aircraft that is unaware of the presence of the UAV itself.	Catastrophic	< 1.0E-7	
	Inability to be visually identifiable and surveillable at night	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot be visually tracked by pilots of other aircraft. This condition causes a reduction in the separation assurance and could lead to the loss of the UAV and fatalities in a mid-air collision with another aircraft that is unaware of the presence of the UAV itself.	Catastrophic	< 1.0E-7	
To exchange data and commands with GCS	Inability to exchange data and commands with GCS when automatic flight capability is lost	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot be controlled remotely by pilots because it does not receive data and commands from the GCS. In addition, pilots could not receive flight/vehicle data. Since the UAV is unable to fly automatically, a fatal accident and loss of the UAV itself can occur.	Catastrophic	< 1.0E-7	Useful information such as overspeed and stall conditions, emergency signals, feedback signals, malfunctions and failures of on-board systems are not exchanged with pilots.
	Inability to exchange data and commands with GCS when automatic flight capability is	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot be controlled remotely by pilots because it does not receive data and commands from the GCS. In addition, pilots could not receive flight/vehicle data. The UAV can continue the mission automatically according to the flight plan or perform an emergency procedure to return to the airport.	Hazardous	< 1.0E-6	Useful information such as overspeed and stall conditions, emergency signals, feedback signals, malfunctions and failures of on-board systems are not exchanged with pilots.
To exchange data with air traffic/ATC satellites/radio NAVAIDs	Inability to exchange data with air traffic	Initial Climb, Climb, Loiter, Descent, Approach	This condition causes a reduction in the separation assurance. If the data is needed to avoid a mid-air collision, the failure condition could ultimately result in the loss of the UAV and human lives.	Catastrophic	< 1.0E-7	
	Inability to exchange data with ATC	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot be identified and surveilled by ATC. This condition causes a reduction in the separation assurance from other aircraft.	Major	< 1.0E-5	
	Inability to exchange navigation data with satellites	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot determine its position.	Major	< 1.0E-5	
	Inability to exchange data with radio NAVAIDs	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot determine navigation information.	Major	< 1.0E-5	
To provide fuel	Inability to provide fuel for propulsion	Take-off	The UAV shuts down and loses thrust. This condition results in a loss of speed, therefore take-off is aborted.	Major	< 1.0E-5	
	Inability to provide fuel for propulsion	Landing	The UAV shuts down and loses thrust. This condition results in a loss of speed during the landing roll.	Minor	< 1.0E-3	
	Inability to provide fuel for propulsion	Initial Climb, Climb, Loiter, Descent, Approach	The UAV shuts down and loses thrust. As a result, it loses altitude. This condition can result in the loss of the UAV and a fatal accident.	Catastrophic	< 1.0E-7	

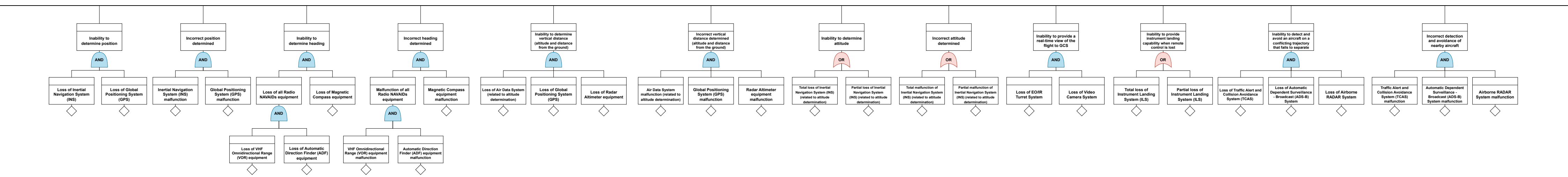
To provide electrical power	Inability to provide electrical power	Taxi	The subsystems of the UAV that require electrical power cannot perform their functions. In particular, the pilots are unable to control the UAV remotely. This condition can lead to a collision on the ground fatally involving people.	**Catastrophic**	**< 1.0E-7**	Taxiing operations are performed at low speeds, therefore a collision should not result in the loss of the UAV.
	Inability to provide electrical power	Take-off, Landing	The subsystems of the UAV that require electrical power cannot perform their functions. In particular, the pilots are unable to control the UAV remotely. Loss of the UAV is possible due to a runway excursion. As a result, people could be involved in a fatal accident.	**Catastrophic**	**< 1.0E-7**	
	Inability to provide electrical power	Initial Climb, Climb, Loiter, Descent, Approach	The subsystems of the UAV that require electrical power cannot perform their functions. In particular, the UAV loses its ability to fly automatically and pilots cannot control it remotely. This condition can lead to the loss of the UAV in an accident that is potentially fatal for people on the ground.	**Catastrophic**	**< 1.0E-7**	
To provide hydraulic power	Inability to provide hydraulic power for braking when required	Taxi, Take-off, Landing	The UAV is unable to decelerate and stop. The severity of the effect of this failure condition can be hazardous or catastrophic.	**Catastrophic**	**< 1.0E-7**	
	Inability to provide hydraulic power for steering when required	Taxi, Take-off, Landing	The UAV is unable to change direction or make direction corrections. The severity of the effects of this failure condition can be hazardous or catastrophic.	**Catastrophic**	**< 1.0E-7**	
To detect fires	Inability to detect fires	Taxi, Take-off, Landing	Emergency procedures cannot be initiated. The loss of the UAV cannot be ruled out.	**Hazardous**	**< 1.0E-6**	A fire on board the UAV during ground operations should not involve people.
	Inability to detect fires	Initial Climb, Climb, Loiter, Descent, Approach	Emergency procedures cannot be initiated. This condition can ultimately result in the loss of the UAV and a fatal accident.	**Catastrophic**	**< 1.0E-7**	
	Incorrect fire detection (false alarm)	Initial Climb, Climb, Loiter, Descent, Approach	This failure condition leads to unnecessary implementation of emergency procedures, therefore the fuel flow could be interrupted for safety reasons. The resulting loss of thrust in flight can lead to the loss of the UAV in an accident, which could fatally involve people.	**Catastrophic**	**< 1.0E-7**	
To prevent ice formation	Inability to prevent ice formation when required	Initial Climb, Climb, Loiter, Descent, Approach	Ice accumulates mainly on the leading edge of the wings, changing the shape of the airfoil. The risk for the UAV is to stall and become uncontrollable. This condition can ultimately result in the loss of the UAV and a fatal accident.	**Catastrophic**	**< 1.0E-7**	
To control payloads	Inability to control primary payload when required	Loiter	The desired images cannot be obtained because the primary payload orientation cannot be adjusted.	**No safety effect**	**No probability requirement**	
	Incorrect primary payload control	Loiter	Accurate images cannot be obtained, as required by the mission.	**No safety effect**	**No probability requirement**	
	Inability to control secondary payload when required	Initial Climb, Climb, Loiter, Descent, Approach	The payload is unable to get a 360° view of the flight, therefore pilots can only observe a part of the external environment.	**Major**	**< 1.0E-5**	
	Incorrect secondary payload control	Initial Climb, Climb, Loiter, Descent, Approach	The payload does not show the required view, therefore pilots observe a wrong view of the flight.	**Major**	**< 1.0E-5**	
To control temperature	Inability to control temperature	Initial Climb, Climb, Loiter, Descent, Approach	The equipment/components of the subsystems requiring cooling to operate could be damaged or could not function.	**Major**	**< 1.0E-5**	Avionics and payloads (sensors) are types of equipment that require thermal cooling.
	Incorrect temperature control	Initial Climb, Climb, Loiter, Descent, Approach	The equipment/components of the subsystems requiring cooling to operate could be damaged or could not function.	**Major**	**< 1.0E-5**	Avionics and payloads (sensors) are types of equipment that require thermal cooling.
To store data	Inability to store flight and vehicle data	All	Flight and subsystem data that can be used in the event of an accident are lost.	**No safety effect**	**No probability requirement**	
	Inability to store payload data	Loiter	Thermal infrared images obtained are lost, therefore the mission is unsuccessful.	**No safety effect**	**No probability requirement**	
To provide parachuting capability	Inability to provide parachuting capability when required	Initial Climb, Climb, Loiter, Descent, Approach	The UAV cannot slow down its fall. This condition can result in the loss of the UAV and a fatal accident.	**Catastrophic**	**< 1.0E-7**	
	Inadvertent parachuting capability provided	Initial Climb, Climb, Loiter, Descent, Approach	The UAV experiences a sudden deceleration and becomes difficult to control (loss of control can occur). This condition can result in the loss of the UAV and a fatal accident.	**Catastrophic**	**< 1.0E-7**	
To provide self-destructing capability	Inability to provide a self-destructing capability when required	Initial Climb, Climb, Loiter, Descent, Approach	A potential crash of the UAV into populated areas cannot be prevented. This condition can result in the loss of the UAV and a fatal accident.	**Catastrophic**	**< 1.0E-7**	
	Inadvertent self-destructing capability provided	All	Loss of the UAV occurs. In addition, the debris produced by the explosion could hit people on the ground causing a fatal accident.	**Catastrophic**	**< 1.0E-7**	

Preliminary Aircraft Fault Tree

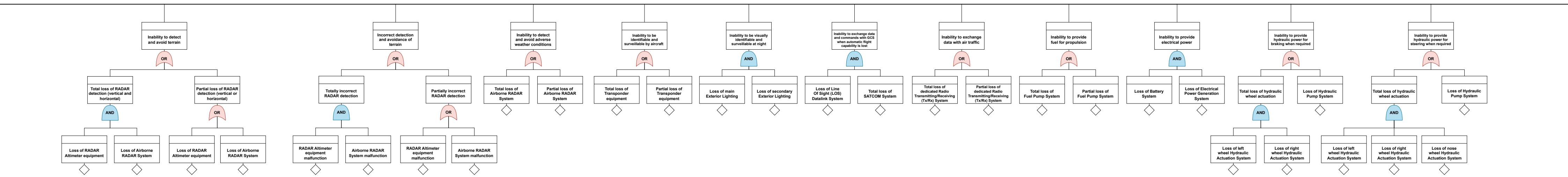




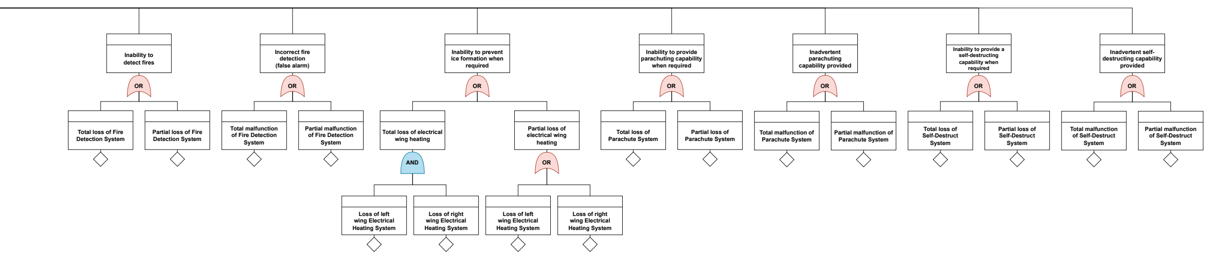
Degraded roll capability
OR
Movement of Ailerons in one direction only
OR
Deflection of right Aileron only upward and deflection of left Aileron only downward
Deflection of right Aileron only downward and deflection of left Aileron only upward
Movement of only a single Aileron in one direction only
OR
Right Aileron deflection only in one direction only
Left Aileron deflection only in one direction only
Degraded pitch capability
OR
Deflection of Elevator only upward
Deflection of Elevator only downward
Degraded yaw capability
OR
Movement of Rudders in one direction only
OR
Deflection of Rudders only clockwise
Deflection of Rudders only counterclockwise
Movement of only a single Rudder in one direction only
OR
Right Rudder deflection only in one direction only
Left Rudder deflection only in one direction only
Incorrect roll movement performed
OR
Incorrect deflection of Ailerons when a left turn is required (opposite movement)
Incorrect deflection of Ailerons when a right turn is required (opposite movement)
Incorrect pitch movement performed
OR
Incorrect deflection of Elevator when climb attitude is required (opposite movement)
Incorrect deflection of Elevator when descent attitude is required (opposite movement)
Incorrect yaw movement performed
OR
Incorrect deflection of Rudders when clockwise yaw is required (opposite movement)
Incorrect deflection of Rudders when counterclockwise yaw is required (opposite movement)
Inability to provide automatic braking capability when remote control is lost
OR
Total loss of Autobrake System
Partial loss of Autobrake System
Inability to provide automatic flight control capability when remote control is lost
OR
Total loss of Autopilot System
Partial loss of Autopilot System
Inability to provide automatic throttle control capability when remote control is lost
OR
Total loss of Autothrottle System
Partial loss of Autothrottle System
Inability to determine airspeed
OR
Total loss of Air Data System (related to airspeed determination)
Partial loss of Air Data System (related to airspeed determination)
Incorrect airspeed determined
OR
Total malfunction of Air Data System (related to airspeed determination)
Partial malfunction of Air Data System (related to airspeed determination)
Inability to determine flight trajectory
OR
Total loss of Flight Management System (FMS)
Partial loss of Flight Management System (FMS)
Incorrect flight trajectory determined
OR
Total malfunction of Flight Management System (FMS)
Partial malfunction of Flight Management System (FMS)



Inability to determine position
AND
Loss of Inertial Navigation System (INS)
Loss of Global Positioning System (GPS)
Incorrect position determined
AND
Inertial Navigation System (INS) malfunction
Global Positioning System (GPS) malfunction
Inability to determine heading
AND
Loss of all Radio NAVAIDs equipment
AND
Loss of VHF Omnidirectional Range (VOR) equipment
Loss of Automatic Direction Finder (ADF) equipment
Loss of Magnetic Compass equipment
Incorrect heading determined
AND
Malfunction of all Radio NAVAIDs equipment
AND
VHF Omnidirectional Range (VOR) equipment malfunction
Automatic Direction Finder (ADF) equipment malfunction
Magnetic Compass equipment malfunction
Inability to determine vertical distance (altitude and distance from the ground)
AND
Loss of Air Data System (related to altitude determination)
Loss of Global Positioning System (GPS)
Loss of Radar Altimeter equipment
Incorrect vertical distance determined (altitude and distance from the ground)
AND
Air Data System malfunction (related to altitude determination)
Global Positioning System (GPS) malfunction
Radar Altimeter equipment malfunction
Inability to determine attitude
OR
Total loss of Inertial Navigation System (INS) (related to attitude determination)
Partial loss of Inertial Navigation System (INS) (related to attitude determination)
Incorrect attitude determined
OR
Total malfunction of Inertial Navigation System (INS) (related to attitude determination)
Partial malfunction of Inertial Navigation System (INS) (related to attitude determination)
Inability to provide a real-time view of the flight to GCS
AND
Loss of EO/IR Turret System
Loss of Video Camera System
Inability to provide instrument landing capability when remote control is lost
OR
Total loss of Instrument Landing System (ILS)
Partial loss of Instrument Landing System (ILS)
Inability to detect and avoid an aircraft on a conflicting trajectory that fails to separate
AND
Loss of Traffic Alert and Collision Avoidance System (TCAS)
Loss of Automatic Dependent Surveillance - Broadcast (ADS-B) System
Loss of Airborne RADAR System
Incorrect detection and avoidance of nearby aircraft
AND
Traffic Alert and Collision Avoidance System (TCAS) malfunction
Automatic Dependent Surveillance - Broadcast (ADS-B) System malfunction
Airborne RADAR System malfunction



Inability to detect and avoid terrain
OR
Total loss of RADAR detection (vertical and horizontal)
AND
Loss of RADAR Altimeter equipment
Loss of Airborne RADAR System
Partial loss of RADAR detection (vertical or horizontal)
OR
Loss of RADAR Altimeter equipment
Loss of Airborne RADAR System
Incorrect detection and avoidance of terrain
OR
Totally incorrect RADAR detection
AND
RADAR Altimeter equipment malfunction
Airborne RADAR System malfunction
Partially incorrect RADAR detection
OR
RADAR Altimeter equipment malfunction
Airborne RADAR System malfunction
Inability to detect and avoid adverse weather conditions
OR
Total loss of Airborne RADAR System
Partial loss of Airborne RADAR System
Inability to be identifiable and surveillable by aircraft
OR
Total loss of Transponder equipment
Partial loss of Transponder equipment
Inability to be visually identifiable and surveillable at night
AND
Loss of main Exterior Lighting
Loss of secondary Exterior Lighting
Inability to exchange data and commands with GCS when automatic flight capability is lost
AND
Loss of Line Of Sight (LOS) Datalink System
Total loss of SATCOM System
Inability to exchange data with air traffic
OR
Total loss of dedicated Radio Transmitting/Receiving (Tx/Rx) System
Partial loss of dedicated Radio Transmitting/Receiving (Tx/Rx) System
Inability to provide fuel for propulsion
OR
Total loss of Fuel Pump System
Partial loss of Fuel Pump System
Inability to provide electrical power
AND
Loss of Battery System
Loss of Electrical Power Generation System
Inability to provide hydraulic power for braking when required
OR
Total loss of hydraulic wheel actuation
AND
Loss of left wheel Hydraulic Actuation System
Loss of right wheel Hydraulic Actuation System
Loss of Hydraulic Pump System
Inability to provide hydraulic power for steering when required
OR
Total loss of hydraulic wheel actuation
AND
Loss of left wheel Hydraulic Actuation System
Loss of right wheel Hydraulic Actuation System
Loss of nose wheel Hydraulic Actuation System
Loss of Hydraulic Pump System



Inability to detect fires
OR
Total loss of Fire Detection System
Partial loss of Fire Detection System
Incorrect fire detection (false alarm)
OR
Total malfunction of Fire Detection System
Partial malfunction of Fire Detection System
Inability to prevent ice formation when required
OR
Total loss of electrical wing heating
AND
Loss of left wing Electrical Heating System
Loss of right wing Electrical Heating System
Partial loss of electrical wing heating
OR
Loss of left wing Electrical Heating System
Loss of right wing Electrical Heating System
Inability to provide parachuting capability when required
OR
Total loss of Parachute System
Partial loss of Parachute System
Inadvertent parachuting capability provided
OR
Total malfunction of Parachute System
Partial malfunction of Parachute System
Inability to provide a self-destructing capability when required
OR
Total loss of Self-Destruct System
Partial loss of Self-Destruct System
Inadvertent self-destructing capability provided
OR
Total malfunction of Self-Destruct System
Partial malfunction of Self-Destruct System