ACTION: Work Package 1

Operational Scenarios, Constraints and Opportunities

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by

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Cover Image: Black Hornet 2 Nano Drone
https://www.drone-zone.de/british-army-zeigt-bug-drohne-mit-sprengsaetzen

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Executive Summary

The aim of the ACTION project is to determine and realise the potential added benefits of integrating acoustic sensors (supported by optical sensors) within the complete chain of detection, identification, and classification of unmanned aerial vehicles (UAVs). As the first stage of the project, operational scenarios need to be defined. Four scenario types are considered: military operations, combat scenarios, critical infrastructure and urban scenarios. This report explores the relevant aspects of the scenarios: UAVs and environment.

Unmanned aerial vehicles, commonly referred to as drones, have four characteristics that are relevant for the ACTION project. These characteristics influence directly or indirectly the sound emission or visibility of the vehicle and therefore lead to constraints on which drones must be targeted within the scope of this project. The weight of the vehicles is limited to maximum 20 kg, which means that nano, micro and mini UAVs must be considered. The size is limited to small and very small UAVs, which means that it varies from the size of a large insect to UAVs with a length of 2 m. Configurations that must be tested are at least the rotary- and fixed-wing UAVs, where the rotary-wing are more likely to fly in urban scenarios and fixed-wing in combat scenarios. The majority of UAVs have electrical power systems, which will be the primary focus of the project. However, engine powered UAVs must not be completely neglected. Furthermore, two types of UAV operations must be considered during experimenting: flight formation (single UAV, multiple UAVs or a swarm) and flight pattern (hover, straight line, loitering, observation pattern, and random patterns). A final relevant feature is the equipment of UAVs. They can carry a variety of sensors, such as optical cameras or radar, and they can carry objects, such as packages or weapons.

The *environment* refers to all other components in the scenarios apart from the UAVs. A survey of the environmental components that affect UAV flyability as well as acoustic and optical sensor performances has been done. The survey motivates consideration of five relevant environmental components, namely the visibility (with and without precipitation), wind speed, daylight condition, urbanisation and land cover, and concurring events. Possible options for each component are quantitatively defined. Associating difficulty scores are assigned to quantify the difficulty of acoustic and optical UAV detection in each condition.

Next, the environmental scenarios are formulated by combining the aforementioned components. A dedicated method has been designed to create a scenario difficulty ranking based upon combined difficulty score for each of these environmental components. This method ensures that all possible scenarios are considered and the difficulty can be quantified for every given test condition on a measurement site. The difficulty is quantified into three different difficulty classes based on the total difficulty score intervals. These difficulty classes are later used to guide the measurement site selection and project planning.

Throughout the duration of this project, measurement campaigns will be organised which all have a defined goal in reaching a certain scenario difficulty class. The difficulty class will increase over time. The campaigns will take place at the Counter-UAS Test Center, former airbase Valkenburg and an urban environment of which its exact location must be determined later.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ACTION	(Project name) ACoustic detecTION of class I (<20 kg) unmanned aircraft systems supported by optical sensors
AGL	Above Ground Level
C&O	Control and Operations
C-UAS	Counter-UAS
DRI	Detection, Recognition, and Identification
ECMWF	European Centre for Medium-Range Weather Forecasts
EO	Electro-Optical
FAA	Federal Aviation Agency
FCS	Flight Control System
FPV	First Person View
FOV	Field Of View
GCS	Ground Control System
HALE	High-Altitude Long Endurance
IMU	Inertial Measurement Unit
IR	Intermittency Ratio
JMG	Joint Meteo Group
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LCZ	Local Climate Zone
MALE	Medium-Altitude Long Endurance
MAV	Micro Air Vehicle
MSL	Mean Sea Level
NATO	North Atlantic Treaty Organization
NLDA	Netherlands Defence Academy
RF	Radio Frequency
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System
VTOL	Vertical Take-Off and Landing
WMO	World Meteorological Organization
WUDAPT	World Urban Database and Access Portal Tools

Symbols

Symbol	Definition	Unit
C	SPL offset for sound event detection threshold	dB
D_{D}	Detection distance	m
K	Sound event detection threshold	dB
$L_{\mathrm{eq.},T,\mathrm{Events}}$	Equivalent event SPL	dB
$L_{\mathrm{eq.},T,\mathrm{Total}}$	Equivalent total SPL	dB
L_{UAV}	UAV size	m
$\mathrm{px.}_{\mathrm{cam.}}$	Optical camera pixel resolution	-
$\mathrm{px.}_{\mathrm{D,req.}}$	Required number of pixels for target detection	-
T	Time span	s
t	Time	s
θ_{FOV}	Angular FOV	deg.

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1 Introduction

1.1. Threats Posed by UAVs

The use of unmanned aerial vehicles (UAVs) has notably grown in the past decade. In 2020, the Federal Aviation Administration (FAA) registered more than ten thousand recreational UAVs per month and has projected that the total number of UAV registrations will triple by 2024 [17]. UAVs offer new possibilities in commercial and recreational sectors, but they can also pose threats. UAVs are attractive for ill-intent use by terrorists due to their relatively low costs and ability to covertly carry harmful objects into target areas that are not reachable by other means [33]. Besides, trespassing and disruptions of critical infrastructures can also (un)intentionally be made by amateur UAV pilots [10]. Many examples of disruptions and security threats posed by UAVs have been witnessed in the past decades. These include crash-landing of a UAV in front of the German Chancellor in 2013 [21] and shutdown of London Gatwick Airport in 2018 because UAVs were spotted close to the runway [4]. Besides, UAVs have also been used in full-scale wars, such as in in the current war in Ukraine [23].

As part of countermeasures to prevent undesirable UAVs, systems for detecting, identifying, and classifying UAVs are urgently needed by governments and defence sectors worldwide. It is clear that such a technology will be required in a wide range of operational scenarios, such as at public events, at critical infrastructure, or in a combat scenario. However, unlike the countermeasures to manned aircraft and ballistic missiles, such a technology is still relatively new [41] and the number of dedicated sensors that is able to detect UAVs in real time is still limited.

1.2. The ACTION Project

The ACTION project, where ACTION stands for ACoustic detecTION of class I (<20 kg) unmanned aircraft systems supported by optical sensors, is a collaborative project among Delft University of Technology (TU Delft), the Netherlands Defence Academy (NLDA), and Embedded Acoustics BV. The main user of the research outputs is the Dutch Ministry of Defence–more specifically, the Counter-UAS (C-UAS) Test Center, which already has several other sensors in use for UAV detection, such as radar and radio frequency (RF) sensors. The aim of the ACTION project has been stated as follows:

> *"The aim of the ACTION project is to determine and realise the potential added benefits of integrating acoustic sensors (supported by optical sensors) within the complete chain of detection, identification, and classification [of UAVs] up to the use of counter measures currently employed by the Ministry of Defence."*

The expected tangible output of the ACTION project is an integrated acoustic and optical system with an embedded algorithm capable of detecting, identifying, and classifying UAVs in "realistic operational scenarios". This system may be deployed in combination with other available sensors. A step-by-step research and development approach is taken to reach these realistic operational scenarios. As the project progresses, the complexity of the sensors, algorithms, as well as the operational scenarios increase to reach real-world operational level.

What are the “realistic operational scenarios” still remains an open question in the early phase of the ACTION project. Therefore, in order to clearly scope the ACTION project, the first work package aims at defining realistic operational scenarios based on a systematic survey of UAVs, environmental conditions, and other sensors which are available and are relevant.

1.3. General Definition of Scenario Types

This report categorises the operational scenarios into four types based on a recent security analysis [54], incidents [40], and consultations with the ACTION project consortium. These scenario types are differentiated based on intention, expected categories of UAVs to encounter, and environment. Broad and qualitative descriptions of each scenario type are provided in Table 1.1. In the subsequent chapters, possible options for the UAVs (Chapter 2) and the environment (Chapter 3) will be examined more quantitatively.

Table 1.1: Qualitative descriptions of the scenario types.

Scenario type	Intentions and examples	UAV	Environment
Military operations  Source: werkenbijdefensie.nl	This scenario describes protection of military bases and missions, such as a patrolling mission, from being observed by reconnaissance UAVs, such as the Black Hornet Nano [43].	For covertness, the UAVs are relatively lightweight and are carrying a camera.	This scenario takes place in a military (air)base or in an open field.
Combat  Source: Balkan (2017) [3]	This scenario describes (terrorist) attacks using UAVs carrying munitions such as a UAV with a handmade grenade launcher captured in Iraq [3]. This scenario is differentiated from the military operations mainly by the intention of the UAVs.	The UAVs are relatively heavy and can vary in types, i.e. fixed-wing and rotary-wing (possibly custom-made) they are likely to carry (homemade) weapons.	This scenario takes place in a military (air)base or in a battle field.
Critical infrastructure  Source: Dmytro S stock.adobe.com	This scenario describes protection of a large-scale infrastructure from being disrupted by UAVs. An example incident is the Gatwick Airport shutdown [4].	The UAVs found in this scenario are likely off-the-shelf rotary-wing UAVs flown by amateur pilots.	This scenario focuses on a large open area with large low-rise buildings. The loudness and intermittency of the background noise vary.
Urban  Source: AP	This scenario describes protection of civilians and VIPs in an urban setting from nuisance and panics caused by UAVs. An example incident is the UAV protest during a press conference of the German Chancellor [21].	The UAVs found in this scenario are likely off-the-shelf rotary-wing UAVs flown by amateur pilots.	This scenario takes place in a built-up area with buildings. The background noise level is expected to be high, depending on the concurring events.

1.4. Framework of the Report

1.4.1. The Big Picture

As mentioned earlier, the final tangible output of the ACTION project is an integrated acoustic and optical sensor system for UAV detection for a realistic operational scenario. A generic schematic of the acoustic and optical sensor system in an operational scenario is provided in Fig. 1.1. The schematic shows that there are several factors in the scenario, including interrelations among these factors, that affect the acoustic and optical detection of UAVs by the sensors. First, the UAV itself as the target—its characteristics such as size and rotor specifications, and operations such as flight pattern affect its acoustic emission, i.e. as a sound source, and visual appearance. Next, the environmental conditions such as the weather conditions and the concurring noisy events impact the sound propagation and the visibility of the UAV to the sensor. Moreover, there can already be other sensors available in the vicinity for the same UAV detection purpose.

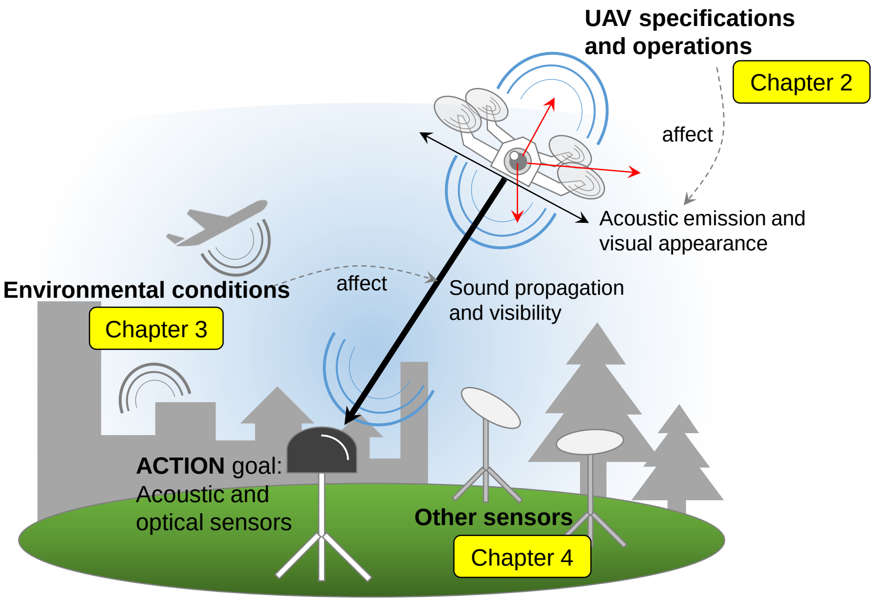


Figure 1.1: Components of the scenarios considered and their relations.

1.4.2. Structure of the Report

Having broadly defined the scenario types in Table 1.1 and outlined the generalised picture of the ACTION system in Fig. 1.1, the components of the operational scenarios, mainly the UAVs and the environment, are examined in more quantitative details. After that, more concrete scenario definitions are formulated. In order to ensure that the scenario complexity increases during the project timeline, and to subsequently assign the scenarios to the project planning, a systematic scenario difficulty ranking is employed.

This report concludes the outcomes of the first work package in the ACTION project: “Operational scenarios, constraints and opportunities”. The structure of this report is illustrated in Fig. 1.2. The qualitative descriptions of the scenario types of interest have been presented in this chapter. Next, Chapter 2 discusses the UAV characteristics, such as weight and configurations, and UAV operations such as flight patterns and formation, followed by surveying the available UAV fleet in the project. Speculations of UAV characteristics to be found in each scenario type are also made. Chapter 3 focuses on the environmental aspect of the scenarios. Possible options for environmental conditions relevant for acoustic and optical detection of the UAVs, such as visibility, urbanisation and land cover, and concurring events, are defined. Next, Chapter 4 summarises available sensors that can potentially be used alongside the acoustic and optical sensors in the ACTION project. Scenario types where these sensors may outperform or would be preferred compared to the acoustic and optical sensors are speculated.

However, it is noteworthy that for defining and quantifying the scenario difficulties in this report, it is assumed that only the acoustic and optical sensors are present. Subsequently, Chapter 5 summarises the options and formulates the operational scenarios. The environmental complexity of the scenarios are quantified by employing a dedicated difficulty ranking system. This ranking provides a guideline for the project planning and test site selection in which the difficulty increases. Finally, the proposed measurement campaigns planning is presented in Chapter 6.

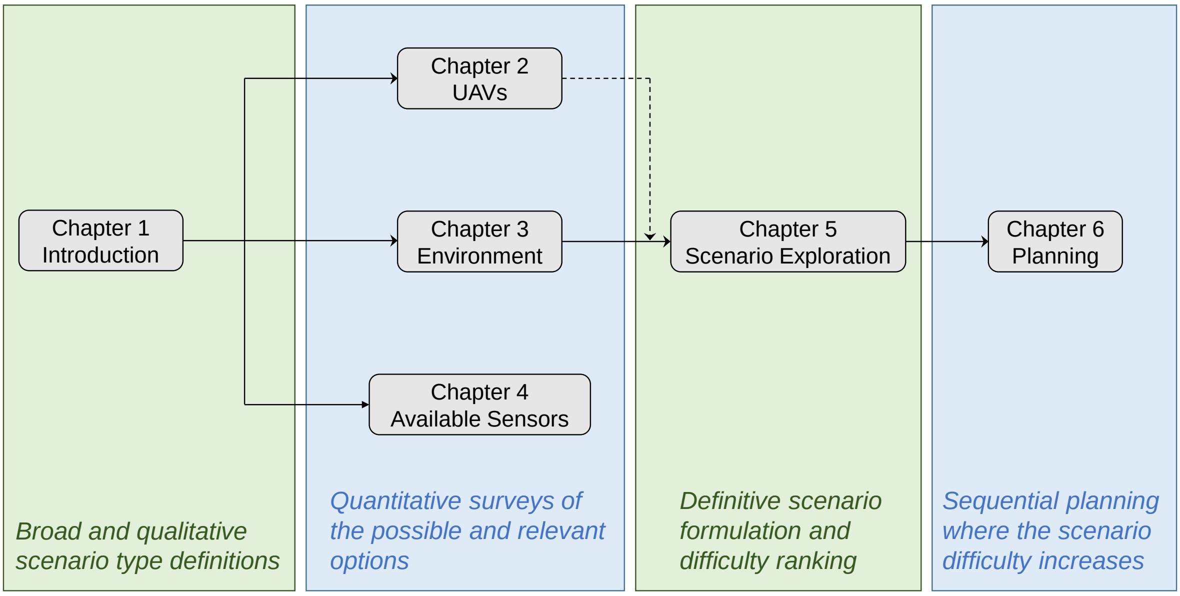


Figure 1.2: Structure of this report.

2

Unmanned Aerial Vehicles

This chapter addresses the central element of Counter-UAS (C-UAS): unmanned aerial vehicles (UAV). In the context of this project, the more common name drone is used interchangeably. A UAV is a subset of the unmanned aerial system (UAS). Apart from the UAV, the UAS may contain a ground control system (GCS), which monitors and/or controls the vehicle. The UAV is equipped with navigation and motion sensors and a flight control system (FCS). Furthermore, in case of manual flight, a communication infrastructure is available between the UAV and GCS to allow for a data link. Drones which fly autonomously do not require such a data link, but need to be programmed before flight to fly a predefined route or towards a predefined target. Lastly, the UAV can be equipped with a payload such as a camera or microphone. However, this is not a requirement for operation [7].

2.1. Characteristics

Usually, UAVs are categorised according to their weight. However, for the ACTION project, it is relevant to consider other UAV characteristics as well, to ensure that a variety of drones with different characteristics are included in the scenarios. This variety is required as a change in characteristics results in different acoustic emissions and visual appearance, as mentioned in Chapter 1. Characteristics that are considered here are weight, size, configuration and motor type. The size directly influences the visibility for the optical systems. Configuration and motor type have large influence on the sound emission of the UAVs. The weight does not have a direct influence on the sound emission or visibility, however it does determine the required thrust and limits the airspeed and operational altitude, which influence the sound created by the motor. Therefore it is included here as well.

2.1.1. Weight

The North Atlantic Treaty Organisation (NATO) has created a classification system of UAS based upon their weight, displayed in Table 2.1 [29]. Some classes can be divided into subcategories, which are written down in the third column. As the scope of the ACTION project is limited to detection of drones lighter than 20 kg, class III has not been fully written out. The UAVs considered in this category are mostly used for reconnaissance for high-altitude long endurance (HALE) and medium-altitude long endurance (MALE) flights. The focus of this project is on the smaller drones, in particular the mini, micro and nano vehicles. According to the NATO classification system, these vehicles fly at altitudes up to 3000 ft ($\sim$915 m) above ground level (AGL) and have a flight radius up to 25 km.

The majority of the consumer drones that are available for recreational purposes fall within the micro category. These are primarily rotary-wing vehicles, which will be discussed later in this section. These UAVs can carry light payload such as a camera or small package. This category will be leading in urban scenarios, during events such as Kingsday, but also for military operations and protection of critical infrastructure. Smaller drones that fall within the nano category are usually used for drone races or military observation with the goal to not be detected, such as the Black Hornet [11]. This category will be of interest for military operations, e.g. patrolling missions. The heavier drones belonging to class I, the mini category, can serve multiple purposes, including long endurance reconnaissance, attacks in

Table 2.1: NATO UAS Classification system.

Class	MTOW	Category	Normal Operating Altitude	Normal Mission Radius
Class III	>600 kg	Strike / Combat, HALE, MALE	Up to 45000 - 65000 ft MSL	Unlimited
Class II	150 kg - 600 kg	Tactical	Up to 18000 ft AGL	200 km
Class I	20 kg - 150 kg	Small >20 kg	Up to 5000 ft AGL	50 km
	200 g - 20 kg	Mini 2 kg - 20 kg	Up to 3000 ft AGL	Up to 25 km
		Micro <2 kg	Up to 200 ft AGL	Up to 5 km
	<200 g	Nano <200 g	Up to 200 ft AGL	Up to 5 km

war areas or observation in urban environment during large-scale events. These are both rotary-wing and fixed-wing UAVs, and especially the latter can carry heavier payload and are therefore suitable for these purposes. This category can therefore be taken into account for multiple scenarios.

2.1.2. Size

The size of a UAV is relevant to consider mainly for optical detection, as larger vehicles will be visible for a larger range. The size of a drone depends on the configuration. The two most common configurations are (multirotor) rotary-wing and fixed-wing, as can be found in the next subsection. Multirotor vehicles are usually characterised by their diagonal size, sometimes accompanied by the length, width and height. Another dimension that is relevant is the rotor diameter. The size of fixed-wing UAVs is usually described by the wingspan, sometimes accompanied by the length, width and height.

There is no international standard for drone categorisation by size. For this project we will therefore use the division proposed by Fahlstrom and Gleason [16] shown in Table 2.2. Although no details related to the weight are provided, it is clear from this table that the scope of the ACTION project is limited to very small and small UAVs. Therefore, it is likely that UAVs that must be detected will have maximum dimensions of about 2 m. On the other hand, there is no clear minimum dimension, however UAVs that have dimensions on the lower spectrum of the very small UAVs should be considered as well.

Table 2.2: UAV classification used by Fahlstrom and Gleason [16].

Class	Dimensions	Configuration
Very Small UAV	Large insect - 30/50 cm	Flapping-wing Conventional (Rotary-wing)
Small UAV	50 cm - 2 m	Fixed-wing
Medium UAV	>2 m Wingspan: 5 - 10 m Payload: 100 - 200 kg	Fixed-wing Rotary-wing (helicopter)
Large UAV	Larger than light manned aircraft Combat operations	Fixed-wing

The drones that fall within the very small UAV category can serve multiple purposes. Most consumer rotary-wing drones fall within this category, as well as the extreme lightweight (nano) drones used for observation in military operations. However, the drones in the small UAV category can also be used in multiple scenarios. They can carry heavier payload and can therefore be used for observation of events or airports, as well as during attacks in combat scenarios. Both categories should be considered for all scenarios.

2.1.3. Configurations

As a result of a variety of mission requirements for (small) UAVs, many UAVs with various shapes and flight modes have been designed over the past decades [25]. According to Shraim et al. [42], three general categories can be distinguished: rotary-wing UAVs, fixed-wing UAVs and flapping-wing UAVs. These will be discussed separately, including advantages and disadvantages of the different types. A summary of the characteristics of the different configurations is provided in Table 2.3, which is taken from the review by Shraim et al. [42], and updated using literature and information from experts of the Counter-UAS Test Center.

Table 2.3: Characteristics of different UAV configurations.

	Rotary-Wing	Fixed-Wing	Flapping-Wing
Manoeuvrability	High	Low	Medium
Energy Consumption	High	Low	Medium
Range	Medium	High	Low
Payload	Medium	High	Low
Civilian Application	High	Low	Low
Military Application	Medium	High	Low
Construction and Repairing	Medium	Low	High
Cost	Medium	Low	High

Rotary-wing

A large number of rotary-wing UAV configurations exist, where the multirotor UAV is the most common one. The majority of the multirotor drones have 2, 3, 4, 6 or 8 propellers. The most used multirotor UAV is the quadcopter, which has 4 propellers. Furthermore, single-rotor UAVs exist, which usually have a similar design and structure as helicopters, only much smaller. The advantages of rotary-wing vehicles are their vertical take-off and landing (VTOL), and hover capabilities. Multirotor vehicles are easy to operate and widely available for recreational use. On the other side, multirotor UAVs have a low endurance and speed compared to fixed-wing UAVs.

Multirotor UAVs form a threat during large-scale events such as Kingsday. There is a large market for these vehicles and they are therefore affordable for recreational purposes. Amateur pilots who are unaware of drone flight regulations can fly these vehicles during such events. One of the concerns regarding these drones on large-scale events is that they cause panic for the audience, leading to unsafe situations. Furthermore, these drones can be used for observation of large areas, such as airports. They are designed for easy attachment of payloads such as a camera for observation, but these can be less heavy than for the fixed-wing counterparts. These vehicles will thus be taken into account mainly for urban and critical infrastructure scenarios.

Fixed-Wing

Fixed-wing UAVs have a large endurance and a long range in comparison to the rotary-wing UAVs. They can fly at higher altitudes and are therefore suitable for reconnaissance or observations, e.g. in agriculture applications. The downside compared to rotary-wing is their manoeuvrability. Furthermore, they need a take-off and landing area.

Fixed-wing UAVs, in particular flying-wing UAVs, form the majority of the threats in combat scenarios.

The reason for this is that these vehicles can lift heavy payload, including weapons. They can fly faster and have a larger endurance compared to multirotor vehicles, which makes them attractive for malicious purposes.

Flapping-Wing
Flapping-wing UAVs are inspired by birds and insects. Most flapping-wing UAVs fall within the micro UAV category, as they are easier to scale down in comparison to rotary-wing and flying-wing UAVs [20]. However, modelling of the unsteady aerodynamics of these vehicles is not trivial, making the design challenging. Therefore only a few commercial flapping-wing UAVs exist.

Flapping-wing UAVs form a low threat in general, due to their low availability. Beside this, they have low payload capabilities, which makes them less interesting for long endurance reconnaissance or observation purposes and combat scenarios. The one scenario where these vehicles could be of interest is military operations. Due to their small size they can perform similar missions as the Black Hornet nano drone. As these UAVs make a completely different sound in comparison to the rotary-wing and fixed-wing UAVs, experiments with a flapping-wing drone should be performed as well.

2.1.4. Motor and Energy Source
For the purpose of detection, it is necessary to look into different motor systems available for UAVs. Different systems produce different sound emissions and they might appear different on optical sensors, such as a thermal imaging camera. The majority of the UAVs use electrical rotors or internal combustion engines [50] as their motor. These two will be briefly discussed below.

Electric rotors
Although some tests have taken place with novel energy sources for electrical systems, such as hydrogen fuel cells and solar power, batteries remain the most popular energy source for UAVs. This is particularly true for micro and smaller UAVs. This is due to their reliability, high efficiency and it results in easier controllability of the drones [25]. Furthermore, the electric rotors that are used together with batteries are relatively small and light-weighted in comparison to internal combustion engines. There are many different types of batteries that can be used onboard of a drone, but the most common ones are Lithium Polymer (Li-Po) and Lithium Ion (Li-ion) batteries [50]. The downside of an electrical power system is the relative short endurance.

Almost all consumer drones are powered by batteries, as well as military drones. Especially drones that fall within the scope of this project need to be light-weighted. Therefore, electrical UAVs powered by batteries must be included in all scenarios.

Internal Combustion Engine
The internal combustion engine power system, which includes engines, fuel and actuators, contributes for 40 to 60% to the take-off weight of the vehicle. [25]. This kind of power system is therefore primarily used for larger, fixed-wing UAVs that are capable of carrying heavier loads and require more endurance. Therefore, the majority of the vehicles that fall within the scope of this project are much more likely to use an electrical power system than a combustion engine. However, there are studies that focus on detection of UAVs lighter than 20 kg which use an internal combustion engine, such as the research performed by Harvey and O'Young [24]. Especially, as the advantage of internal combustion engine UAVs is the higher endurance, it is useful to also perform experiments with such a vehicle. The scenarios where this would be relevant are combat scenarios.

2.2. UAV Operations
Apart from the characteristics that influence acoustic and optical detection, UAV operations also affect the detection through these sensors. Two operations are considered in this project: flight formation and flight pattern. These operations have a large influence on both the detection through acoustic and optical sensors.

2.2.1. Flight Formation

One aspect that is relevant for acoustic and optical sensors for UAV detection is the amount of UAVs that enter or are present in an area. In the remainder of this project we call this the flight formation and we distinguish three categories: single UAV, multiple UAVs and a swarm of UAVs. What is meant by these categories is described below.

Single UAV and Multiple UAVs

The most straightforward scenario is the intrusion of a single UAV into a forbidden area. However, to test the limits of the detection systems, it is necessary to perform experiments with other formations, where multiple drones intrude the area from the same direction or multiple directions. To investigate the capabilities of the acoustic system to discriminate among multiple drones, these experiments should be performed with a variety of drones as well as with multiple drones of the same type. It should be investigated how similar emissions from multiple vehicles are received by the microphones and if it is possible to discern between several drones in the processing of the data. Also from an optical point of view it should be checked if it is possible to distinguish between different vehicles. Another aspect here that should be determined is what the optical system must do if there are multiple drones from different directions, but there are not sufficient cameras to follow all of them. Lastly, both options of a single UAV or multiple UAVs formation are relevant for all scenarios.

Swarm of UAV

A swarm of drones can be described as a set of UAVs that work together to achieve a specific goal [48]. The difference between a swarm of drones and multiple drones flying within a forbidden area is that in a swarm the drones cooperate. This cooperation can be different for each swarm. Some swarms have a leader drone that is flown manually, or the drones can fly a predefined path autonomously. It is also possible to equip different drones with different sensors, such that data from all individuals complement each other. The challenge for detection of a swarm is that the drones are usually the same leading to similar sound emissions, they might fly close to each other and they might perform similar movements. This will make it hard to discern them as multiple drones. At the Counter-UAS Test Center, it is not yet possible to fly drones in a swarm.

Swarms are used for multiple purposes, such as for exploration or observation of (large) areas, as well as for amusement during drone shows. However, they are also used for military purposes, where a swarm of drones is used for an attack. It should be noted that flying a swarm of drones requires advanced systems and knowledge about drones, which is usually not available for recreational purposes. Therefore, swarms are not the main threat for urban scenarios, but it should be taken into account for combat scenarios.

2.2.2. Flight Patterns

The flight patterns influence both the sound emission and visibility on optical sensors. Sound emissions are influences by the thrust setting and as drones are not monopoles, the attitude influences the received sound signature at microphone level. Attitude is also relevant for the optical system, as well as the speed of the vehicle as this influences the tracking capabilities. Therefore flight patterns can be generalised in terms of the flight speed and attitude vectors of the UAV. To limit the scope of flight patterns for the first experiments, a set of basic manoeuvres is drafted here. The Counter-UAS Test Center does not have a specified set of manoeuvres it flies to test new detection systems. The flight patterns are usually chosen such that it tests the weak points of the system that is tested.

Hover

The easiest flight pattern is hovering at one specific location. This manoeuvre can only be performed by rotor and flapping-wing UAVs. Hovering should be performed at different heights and distances from the acoustic and optical sensors. Furthermore, it should be tested if the vehicle can still be detected if it is hovering in the vicinity or behind obstacles. To test the tilting mechanism of the optical sensors, experiments at extreme angles, such as directly above the optical sensor, should be performed. To test the boundaries of the acoustic sensor, it should be tested in line or below the microphone plane.

Straight Line

Another straightforward pattern is flying a straight line. This should be tested again at different altitudes and distances from the sensors. This manoeuvre might also include a climb and descent phase. For this scenario it is also required to test the boundaries of the detection system, which means e.g. that the flights must be performed at the edge of the detection range of the acoustic sensor. Another point of attention is that the experiment should be performed at different flight speeds, as this influences the sound emissions due to different thrust settings as well as the tracking capabilities of the optical sensors. This should be included in urban, critical infrastructure and combat scenarios. During military operations, when the purpose is observation without being noticed, it is usually not desired to fly at fast speeds, and therefore the detection system is not used up to its boundaries in this scenario.

Advanced Manoeuvres

Next to the above mentioned patterns, other patterns can occur as well. A rotor UAV can hover above a point it would like to observe. However, fixed-wing UAVs cannot hover. These vehicles must loiter in circles or a holding pattern for observation. Another goal for intruding UAVs is observation of the full area, where coverage path planning plays a role. For regular-shaped, non-complex areas simple patterns are sufficient, which are shown in Fig. 2.1 [5]. The most common ones are the back-and-forth and spiral patters, which are shown in Fig. 2.1(a) and 2.1(b), and Fig. 2.1(c). Apart from these simple patterns, more complex patterns exist for both regular-shaped and complicated areas, where e.g. energy consumption of the vehicle(s) is minimised. However, for these patterns the complicated areas are usually divided into sub-areas in which the UAV(s) flies (fly) again in a back-and-forth or spiral pattern. For detection it is therefore sufficient to focus on these basic patterns only.

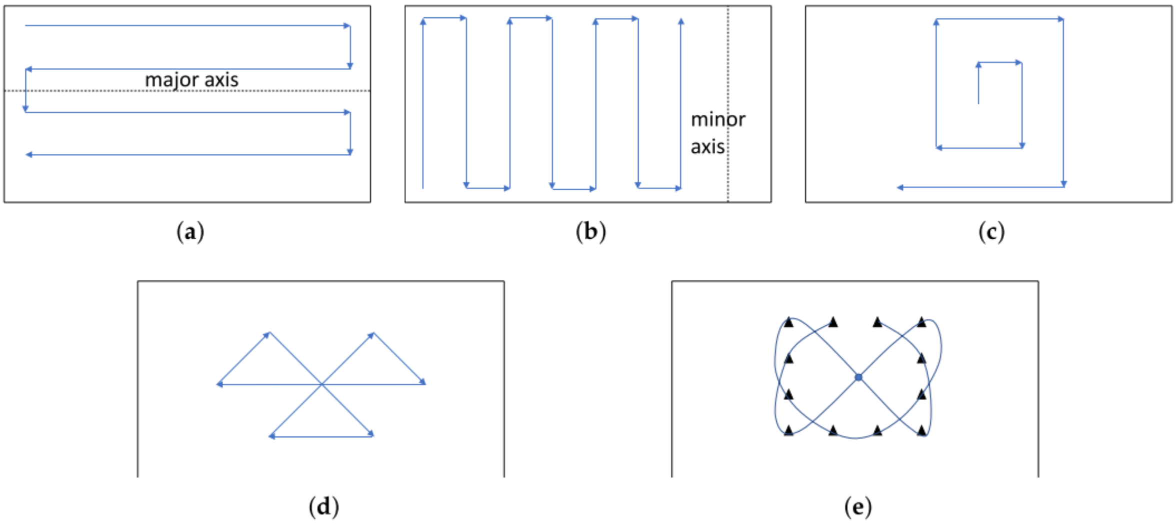


Figure 2.1: Simple flight patterns for observation in rectangular area: (**a**) Parallel; (**b**) Creeping Line; (**c**) Square; (**d**) Sector Search; (**e**) Barrier Patrol [5].

It is likely that drones will fly different patterns during all scenarios, however for consistency and testing the capabilities of the detection systems it is good to include all the above mentioned flight patterns for all scenarios. Beside this, more flexible flights should be made, where the limits of the detection system are tested. This means that more abrupt movements should be made, as well as flights with large altitude and attitude changes. For this the general representation flight patterns in terms of its speed and attitude vector can be used.

2.3. UAV Equipment

Another feature related to UAVs that is of interest for the ACTION project is the equipment of the vehicle. For normal operation, several sensors are required. However, apart from these, other sensors or payloads can be attached as well. In this section the most common ones or those that form the largest threat for one of the four discussed scenarios will be discussed briefly.

2.3.1. Sensors

In order to operate, a UAV requires accelerometers and gyroscopes, usually packed together in the Inertial Measurement Unit (IMU). A GPS is not necessarily required if the initial position and velocity are known, although this will lead to inaccuracies when integrating for velocity and position during flight due to measurement noise. Therefore, usually magnetometers and GPS are used as well [2]. The flight control system maintains level flight or executes commands from the pilot using information from the IMU. Due to measurement errors and unreliable GPS signals in dense or indoor environments, other sensors can be added to support the vehicle during critical phases such as landing. These can be optical cameras, ultrasonic technology, stereo vision and infrared [2].

Beside sensors for onboard position determination, many other sensors can be attached to the vehicles for e.g. observation, monitoring, and sensing and avoiding capabilities. Sensors that can be used for this are optical (RGB) cameras, thermal (infrared) cameras, event-based cameras, light detection and ranging (LiDAR) sensors, radar, acoustic sensors, and many more, including different variants of the previously mentioned sensors. Drones can nowadays even be equipped with gas sensors [15]. Different sensors have a different shape and size, and possible thermal radiation, which can influence the detection of the vehicle using optical sensors. It is therefore useful to test drones with different sensors during the experiments.

2.3.2. Payload

Apart from sensors, drones can also carry payloads. These are not meant for measurement purposes, but in these situations the drone is purely a carrying mechanism to bring an object from one location to another. Different objects are possible, such as a package for cargo delivery or weapons. Especially the latter is relevant for the ACTION project, as this is a large threat during combat scenarios. Payloads influence the shape of the UAV on an optical sensor. Furthermore, depending on the weight of the payload, the sound of the drone is also altered, as it requires more lift to remain in the air, which in turn influences the power system and its noise. Therefore it is necessary to perform experiments with UAVs carrying payloads. At the Counter-UAS Test Center a dummy payload can be used, which is a light-weight, white foam object. However, to ensure a large variety of optical and sound signatures, more payloads must be used.

A final point of attention regarding weaponized UAVs is that there are also UAVs that are already a weapon themselves. These vehicles are called loitering munitions and can be described as “low-cost guided precision munitions that can be maintained in a holding pattern in the air for a certain time and rapidly attack land or sea non-line-of-sight targets” [52]. These vehicles also fall within the category of UAVs that must be detected within the ACTION project. However, most loitering munitions have configurations that fall within the categories defined in Subsection 2.1.3. Although more configurations are mentioned in the 2022 study by Voskuijl [52], for the scope of this project most of these fall within the fixed-wing category. It is thus expected that both the optical and sound signature are similar to those from conventional UAVs and therefore it is not necessary to do flight tests with these kind of vehicles.

2.4. Available UAVs

There are two parties involved in the ACTION project who have UAVs available for the measurements and tests: the Counter-UAS Test Center and the Faculty of Aerospace Engineering. The details of these vehicles are described below. Using the listed drones and previous described categories possible gaps can be identified that would obstruct tests for the scenarios drafted in Chapter 5. In case large gaps are present, there is budget within the ACTION project to fill these and buy additional UAVs.

2.4.1. Counter-UAS Test Center

The UAVs that are available at the Counter-UAS Test Center are tabulated in Table 2.4. All vehicles except one are quadrotors. All quadrotors, except the Skyranger R70, are consumer drones made for recreational purposes. The Skyranger R70 is specifically made for military purposes. This drone can be attached to a power line and can hover for a long period of time, beyond the normal battery life.

Table 2.4: UAVs available at the Counter-UAS Test Center.

UAV	Type	Weight	Max Speed [m/s]	Max Flight Time [min]	Max Distance to Base
DJI Mini 2	Quadrotor	242 g	16	31	6 km
DJI FPV	Quadrotor	795 g	39	20	10 km
DJI Mavic 3	Quadrotor	895 g	19	46	15 km
Autel EVO II	Quadrotor	1191 g	20	40	9 km
DJI Phantom 3	Quadrotor	1216 g	16	25	1000 m
DJI Phantom 4	Quadrotor	1380 g	20	28	3500 m
Skyranger R70	Military Quadrotor	5 kg	14	40	8 km
Parrot Disco FPV	Fixed-Wing	750 g	22	45	2000 m

One interesting observation that can be made from this table is that the Counter-UAS Test Center owns a large number of quadrotors. The reason for this is that these vehicles are often used for recreational purposes and therefore form the largest threat during large-scale events belonging to urban scenarios. The core task of the Netherlands Armed Forces is National Operations [12], and therefore the focus of the C-UAS Test Center is mainly on detection and elimination of rotor vehicles. However, the Test Center would like to have additional fixed-wing drones to be better prepared for combat scenarios, but due to low market availability, they are not easy to source.

2.4.2. Faculty of Aerospace Engineering

Within the department of Control and Operations (C&O), many UAVs are available. The majority of these drones belong to the Micro Air Vehicle (MAV) lab, where a lot of research is performed on different types of drones and with a variety of objectives. This means that not only consumer drones are available, but also custom-made drones created by the engineers of the MAVLab. This results in a large variety of drones, with large difference with the ones available at the C-UAS Test Center. The MAVLab engineers perform outdoor tests on a regular basis at the former airbase Valkenburg. A list of consumer or off-the-shelf drones that are available at the C&O department are listed in Table 2.5.

Table 2.5: UAVs available at the Control and Operations Department.

UAV	Type	Weight	Max Speed [m/s]	Max Flight Time [min]	Max Distance to Base
Emax Tiny Hawk	Quadrotor	43.5 g	-	7	400 m
Parrot Mambo	Quadrotor	63 g	-	9	20 m
Parrot Anafi	Quadrotor	320 g	15	25	4000 m
Parrot Bebop 1	Quadrotor	420 g	13	11	250 m
Parrot Bebop 2	Quadrotor	420 g	18	25	300 m
Parrot AR.Drone 2.0	Quadrotor	420 g	10	12	50 m
Flapper Drone	Flapping-Wing	100 g	-	5	-
Horizon Hobby X-VERT VTOL	Fixed-wing	200 g	-	8	-
Parrot Disco FPV	Fixed-Wing	750 g	22	45	2000 m
Gatewing X100	Fixed-Wing	2 kg	20.8	45	5 km
DelftAcopter	Fixed-Wing	4.3 kg	25.5	-	-

Apart from the UAVs mentioned in this table, several custom-made UAVs can be used during experiments as well. These are primarily fixed-wing vehicles, some with additional characteristics such as rotating wings. These features make them interesting to experiment with, to ensure a large variety of sound signatures in the final database. Most of these vehicles are made of a light-weight foam. Last of all, the faculty owns one UAV working with an internal combustion engine. Although this UAV weighs 24.9 kg, which is outside the scope of this project, it can still be useful to perform a test with it, to obtain at least one sound signature of an internal combustion engine powered UAV.

3 Environment

Referring back to Fig. 1.1, the term *environment* entails all of the surroundings in the scenarios, apart from the UAVs and their manoeuvres described previously in Chapter 2. This chapter provides a shortlist of environmental components that are of potential interest for formulating the scenarios.

3.1. Components of the Environment

Firstly, the environment components are defined. Next, all possibilities of each component are explored. Finally, a shortlist of possibilities for each component is provided based on their relevance and realisation feasibility within the ACTION project.

The environment is subdivided into three components as presented in Fig. 3.1. Further elaboration for each component is provided in the following.

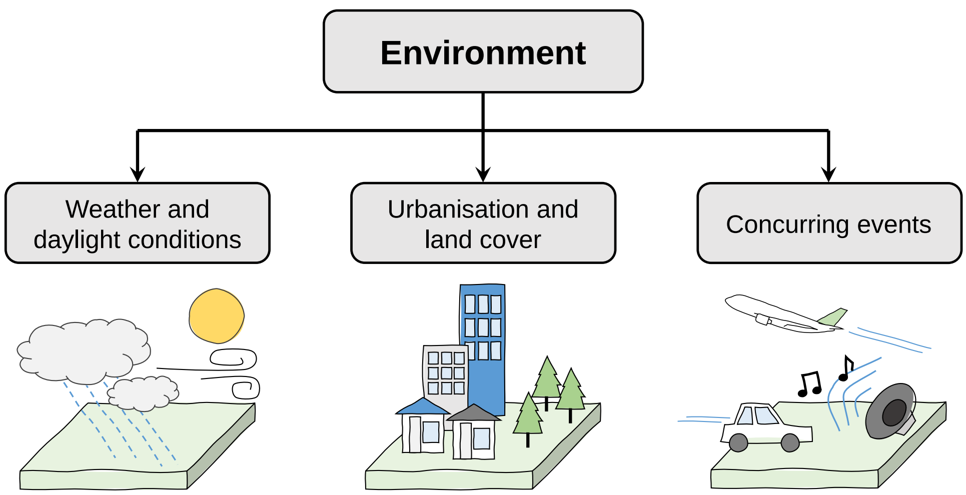


Figure 3.1: Considered components of the environment.

- **Weather and daylight conditions**: This entails the meteorological parameters, wind speed, visibility (with and without precipitation), and daylight conditions.
- **Urbanisation and land cover**: This entails the types of land use and terrain.
- **Concurring events**: This entails human activities occurring in the environment simultaneously with the UAV operations.

Having defined the environmental components, each component is systematically explored in more detail in the subsequent sections. The options for each component are combined in Chapter 5 to formulate the scenarios.

3.2. Weather and Daylight Conditions

The weather and daylight conditions considered in the scenarios must be an overlap of the flyable conditions for the UAVs, and conditions that impact performance of the acoustic and optical sensors–the sensor types that are of the highest interest for the ACTION project. A diagram representing this down-selection concept is shown in Fig. 3.2.

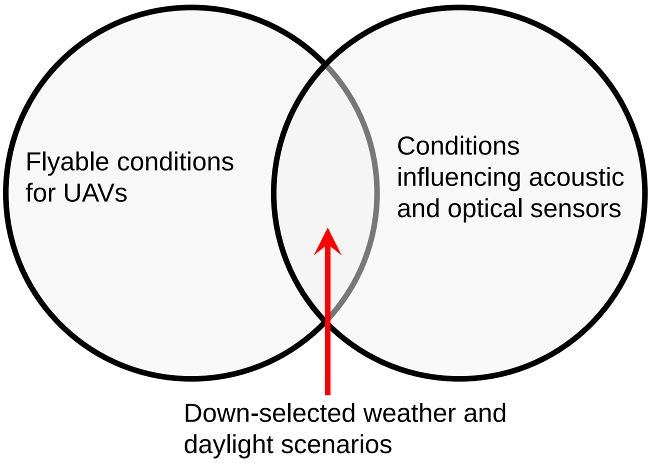


Figure 3.2: Down-selection of the weather and daylight conditions.

3.2.1. Weather and daylight conditions influencing UAV flyability

A recent report of Gao et al. [22] provides an extensive analysis to quantify weather-dependent flyability for small UAVs ($<$ 25 kg). There are three weather constraints for UAV flyability: i.) temperature, ii.) wind-speed, and iii.) precipitation. The report provides a survey for the range of the aforementioned parameters, in which the most frequently registered UAV models [top 50 models, representing 69% of the total registrations according to the Federal Aviation Agency (FAA)] are flyable. The ranges of each parameter are discussed in the following.

1. Temperature: Among all the surveyed UAVs, the Lockheed Martin Indago 3.1 has the lowest minimum operational temperature of -34°C, while the DJI Matrice V2 models have the highest maximum operational temperature of 50°C. The other UAV models are flyable within a range of, in average, -20°C to 45°C. Even without adding contingencies, this temperature range is already much larger than the average minimum and maximum temperature in most places, and is also likely to be comparable to the operational temperature ranges of the acoustic and optical sensors. Therefore, the operational temperature range is not likely a relevant constraint for scenario definitions, and will further be neglected.
2. Precipitation: The majority of the surveyed UAVs are not water resistant, while most water-resistant models can tolerate up to 10 mm/h precipitation. The most water-resistant UAV in the survey is the Zipline Zip model which claims to be operable up to 50 mm/h precipitation. The precipitation constraint for the UAVs is likely an active constraint for scenario selection. The upper bound for the precipitation rate is taken as 12.5 mm/hr when defining the scenarios. This is equivalent to an average rain.
3. Wind speed: Although distinctions shall be made between the average wind speed and the wind gusts, i.e. sudden increase of the wind speed for a period of less than 20 seconds [1], UAV manufacturers nowadays still report the maximum wind speed tolerance without a clear indication whether this refers to the gust or the sustained wind [22]. However, to proceed, this report assumes that the term *wind speed* refers to the maximum wind speed encountered regardless of the duration. The maximum wind speed resistance is dictated by the maximum flight speed, which is in turn dependent on the particular UAV specifications—specifically, the thrust-to-weight ratio [14]. Among all of the surveyed UAVs, the Parrot Bebop 2 model claims to have the highest maximum wind speed resistance of 17 m/s (Beaufort scale number 7). The wind speed is also likely

an active constraint for the scenario selection. To account for future technological developments and outliers, a contingency is added to increase the maximum operable wind speed resistance to 20.7 m/s (Beaufort scale number 8, i.e. one step higher). This is taken as the upper limit for the wind speed when defining the scenarios. Nevertheless, it is expected that most scenarios in practice will not exceed the wind speed of 4-5 on the Beaufort scale, which is the upper limit for average UAVs.

Apart from the weather conditions, the daylight condition also limits the UAV flyability. According to the FAA Drone Regulations (Part 107.29) [18], most UAVs are not allowed to operate at night unless certain strict conditions are met. However, this is a legal constraint rather than a technical constraint as for the weather conditions. Ill-intent UAVs can still be operated at night. Therefore, both daytime and nighttime shall be considered in the scenario definitions.

3.2.2. Weather and daylight conditions influencing acoustic and optical sensor performances

Assuming that no other sensor is present, the final UAV detection system resulting from the ACTION project will consist of, at the minimum, acoustic and optical sensors. Weather and daylight conditions that impact performances of such sensors shall be considered for the scenario definitions. Relevant weather and daylight conditions that impact the acoustic and optical performances are derived from the Review of Current Counter UAS Framework report by Życzkowski et al [56].

Acoustic sensors, i.e. microphones, may be affected by the wind speed and the precipitation. The effect of the wind speed is twofold. First, the wind induces microphone self noise, which hinders the acoustic detection of the UAV. This is the case even for shielded microphones. Van den Berg [51], Strasberg [46], and many authors have shown that microphone self-noise increase is a frequency-dependent function of the wind speed and wind shield diameters. The broadband A-weighted Sound Pressure Level (SPL) in dB of the wind noise is known to vary with a factor of 4.4 to 6.8 times the wind speed in m/s [28]. Second, the wind causes diffraction of the sound propagation from the UAV to the acoustic sensor. Strong deviation of the acoustic propagation path and subsequently the measured sound level can be found in comparison to the no-wind condition. The largest deviation is expected when the acoustic sensor is placed upwind of the UAV. In some cases, this could result in the acoustic sensor being in the so-called *shadow zone* [27]. Therefore, as far as acoustic sensors are concerned, the wind speed is an important component in defining the scenarios. Additionally, water accumulation induced by precipitation in the wind shield may reduce the sensitivity of the microphone.

Under ideal weather and daylight conditions, the sensor-to-target distance where a UAV can be detected depends on the resolution of the optical sensor, the size of the UAV, and the angular field of view [47]. Many commercial manufacturers of optical sensors for UAV detection claim to be able to detect a UAV up to a distance of 10 km [56]. However, it is not usually clear what size of the UAV their claims are referring to. Instead, to help to quantify the expected maximum UAV detection distance, a calculation method is provided in Appendix A. Under non-ideal visibility and daylight conditions, this maximum distance is reduced. Therefore, visibility and daylight conditions are two additional relevant factors to consider for the scenario definition. It is noteworthy that the visibility reduction can also be caused by precipitation.

The operational temperature ranges for acoustic and optical sensors are likely to be comparable to that of the UAVs as discussed in Subsection 3.2.1, and can be neglected for the same reasoning.

3.2.3. Shortlist of weather and daylight conditions including data resources

From the discussions in Sections 3.2.1 and 3.2.2, relevant aspects of the weather and daylight conditions to be considered in the scenarios have been identified. To summarise, there are three aspects to be considered:

1. Visibility
   (a) Visibility without precipitation
   (b) Visibility with precipitation

2. Wind speed
3. Daylight conditions

Visibility
The World Meteorological Organization (WMO) defines 'visibility' as "the greatest distance at which a black object of suitable dimensions (located on the ground) can be seen and recognised when observed against the horizon sky during daylight or could be seen and recognised during the night if the general illumination were raised to the normal daylight level" [36]. Visibility is therefore reported in terms of distance. The distance is further subdivided into intervals and the so-called WMO 4300 codes are assigned to describe the visibility.

Visibility can be reduced by multiple factors. Without precipitation, visibility could be reduced by fog, haze, dust, smoke, etc. In most of these conditions, UAVs can still operate. However, visibility could also be reduced when there is precipitation. Under this latter circumstance, most UAVs are not flyable. According to Subsection 3.2.1, most UAVs are not flyable under the precipitation rate of more than 10 mm/h, hence making it impossible to define test scenarios above this limit. Therefore, for defining scenarios, the precipitation is taken into account first, then the visibility is subdivided into intervals based on potential difficulties it imposes on acoustic and optical sensors.

When there is no precipitation, three visibility intervals are defined: low, medium, and good visibility. These are shown in the left hand side of Table 3.1. The corresponding distance ranges and WMO 4300 codes are also shown on the two rightmost columns. The upper limit of the low-visibility condition corresponds to the international definition of fog, where the maximum visibility is less than 1 km [35]. However, causes of visibility lower than 1 km are not limited to fog. Other causes, such as smoke, are also possible. The medium visibility corresponds to the range between 1 and 10 km, and good visibility means visibility above 10 km. Next to these visibility intervals, a corresponding difficulty scale is assigned to the acoustic and optical sensors. This is a rough estimation scale with three difficulty levels: low, medium, and high. The purpose of this scale is for further ranking of overall scenario difficulty. The corresponding scales are also specified in Table 3.1.

Next, when there is precipitation, only two intervals are identified due to the UAV flyability constraint. According to the International Visibility Code, in light rain or snow, associated with a precipitation rate up to 2.5 mm/h, the visibility may be reduced to 4 km [55], while a relatively better visibility is possible in drizzling conditions with a precipitation rate up to 0.25 mm/h. Two corresponding visibility conditions are therefore defined and the corresponding difficulties for acoustic and optical sensors are specified in Table 3.1.

In summary, there are five options to formulate a scenario based on the visibility. For convenience, a unique nomenclature is assigned to every option. The nomenclatures are also shown in Table 3.1, written in **bold**.

As far as the visibility is concerned, ill-intent UAVs flown by experienced pilots in the military operations and the combat scenarios may make use of the poor visibility to avoid being detected. Therefore, it is important to consider all levels of the visibility in these two scenario types. On the other hand, for the critical infrastructure, and especially the urban scenarios, the visibility condition is more likely to belong to the 'medium' to 'good' visibility subcategories only.

There are multiple resources for the visibility and the precipitation information during the measurements in the ACTION project. The resources include the open-data from the Royal Netherlands Meteorological Institute (In Dutch: KNMI, Koninklijk Nederlands Meteorologisch Instituut), where, among many other parameters, the retrospective visibility (in km) and precipitation rate (in mm/hr) information measured at 50 weather stations throughout the Netherlands every 10 seconds are publicly accessible. Information from the closest weather station to the measurement site can be used. A possible option for the weather forecast is that obtained from the Joint Meteo Group (JMG) of the Ministry of Defence. The data is available in the so-called 'METGM' format, which is a weather forecast generated based on information from weather stations worldwide provided by the European Centre for Medium-Range

Weather Forecasts (ECMWF). The information is released every 12 hours.

Table 3.1: Visibility descriptions for the scenarios.

No precipitation				Precipitation						Visibility	WMO 4300 code
Own terminology	Difficulty for acoustics	Difficulty for optics	Weather conditions	Own terminology	Difficulty for acoustics	Difficulty for optics	Precipitation types		mm/h		
No precip. Low visibility **P0&V1**	Low	High	Dense fog	(Not possible to fly most UAVs)						0 - 50 m	0
			Thick fog							50 - 200 m	1
			Moderate fog							200 - 500 m	2
			Light fog				Snow	Storm	100	500 - 770 m 770 - 1000 m	3
No precip. Medium visibility **P0&V2**	Low	Medium	Thin fog					Strong rain	25	1 - 1.9 km 1.9 - 2 km	4
			Haze					Average rain	12.5	2 - 2.8 km 2.8 - 4 km	5
			Light haze	Precip. Medium visibility **P1&V2**	Low	Medium		Light rain	2.5	4 - 5.9 km 5.9 - 10 km	6
No precip. Good visibility **P0&V3**	Low	Low	Clear	Precip. Good visibility **P1&V3**	Low	Low		Drizzle	0.25	10 - 18 km 18 - 20 km	7
			Very clear							20 - 50 km	8
			Exceptionally clear							50+ km	9

Wind Speed
For scenario definitions, the wind speed is subdivided into three intervals, i.e. levels, and named as low, medium, and high winds. The speed ranges for each level are shown in Table 3.2. The nomenclature and the difficulty scale for the acoustic and optical sensors for each option are also assigned for further scenario difficulty ranking. As discussed earlier, the wind speed is expected to heavily impact the acoustic sensor performance as it affects both the acoustic propagation and the self-noise of the acoustic sensor. Therefore, the difficulty level increases with the increasing wind speed. The wind speed information at the weather stations is available in the aforementioned KNMI open data. Additionally, a portable anemometer is commonly used by drone pilots to measure the local wind speed. Therefore, accurate on-location wind speed information can easily be recorded during the experiments.

Similarly to the visibility condition, the military operations and the combat scenarios are likely to take place during all the wind-speed conditions. This is because the UAVs are likely flown by experience pilots and can endure strong winds. However, for the critical infrastructure and urban scenarios in which off-the-shelf UAVs are likely flown by amateur pilots, it is likely that the wind speeds will fall under the 'low' to 'medium' ranges only.

Table 3.2: Categorisation of wind speeds.

Own terminology	**Wind speeds**	**Difficulty for acoustics**	**Difficulty for optics**
Low wind **W1**	0 - 3.3 m/s (Beaufort number 0-2)	Low	Low
Medium wind **W2**	3.4 - 10.7 m/s (Beaufort number 3-5)	Medium	Low
High wind **W3**	10.8 - 20.7 m/s (Beaufort number 6-8)	High	Low

Daylight conditions
Three daylight conditions are considered: nighttime, twilight and low sun, and daytime. These are summarised in Table 3.3. The daylight conditions are subdivided based on the solar angle with respect to the horizon. This information can simply be obtained based on the local time and location where the measurements take place. Again, the difficulty scale for the acoustic and optical sensors are assigned to further help rank the scenario difficulties. It is expected that all the daylight conditions can be found in all of the scenario types.

Table 3.3: Categorisation of daylight conditions.

Own terminology	**Solar angle with respect to the horizon**	**Difficulty for acoustics**	**Difficulty for optics**
Nighttime **D1**	$< -18°$	Low	High
Twilight and low sun **D2**	$\geq -18°$ and $< 6°$	Low	Medium
Daytime **D3**	$\geq 6°$	Low	Low

3.3. Urbanisation and Land Cover

Physical complexity of the surroundings is also pivotal for defining the scenarios. This is because the acoustic and optical sensors are affected by complexity of the environment. For acoustics, physical objects may alter and/or reflect sound propagation. For optics, visual complexity of the environment [32, 39] could complicate UAV detection. UAVs intending to camouflage may benefit from the background complexity. Research has shown that optical recall of UAV drop substantially if the background of the UAV are dense trees instead of a clear sky [9]. Physical complexity of the environment can be caused by multiple factors. In non-urbanised areas, the complexity may depend on, for instance, tree canopy and density. On the other hand, in urbanised areas, the complexity also varies with building density and height. Nevertheless, for scenario definitions, physical complexity must objectively be quantified. This should be done to a level where objective classification of the test site, based on its physical complexity, can be made.

For this purpose, the Local Climate Zone (LCZ) system is used. The LCZ is a classification system recently proposed by Steward and Oke [45]. It provides a standard urban landscape classification method that takes into account the physical features of the environment, such as building density and height, land cover, etc. Although the LCZ has originally been designed for urban climatology studies, it also provides an excellent framework for the scenario definition in the ACTION project. The LCZ system first subdivides land use types into two major types: built and land-cover types. Next, each type is subdivided into multiple classes. For the built type, numeric values from 1 to 10 are assigned to different classes depending on building densities, sizes, and heights. For the land-cover type, alphabets from A to G are used to designate the classes. A summary of the LCZ types and their classes are shown in Fig. 3.3. Strict quantitative criteria, such as average building height and surface area, are used to categorise the physical attributes of the environment into these LCZ classes.

The LCZ framework is an internationally accepted classification that has been used in a broad range of research from climatology to machine learning. The so-called World Urban Database and Access Portal Tools (WUDAPT) have been initiated to facilitate worldwide sharing and accessing the LCZ data. The LCZ database of Europe is publicly accessible via this portal [13].

As a general example, the LCZ data map of Amsterdam and its surroundings is shown in Fig. 3.4. It is expected that the physical complexity in the centre of Amsterdam is high since it is a highly urbanised zone. Correspondingly, this zone belongs to LCZ classes 2 to 5, i.e. from open to compact midrise. This is likely the surrounding for the urban scenario type. The less complex suburban areas of Amsterdam including the Westport in the northwest and Schiphol International Airport, which are the critical infrastructures, in the southwest clearly contain a different set of the LCZ classes, namely, classes 6-10, and E. Another example considered is the Luitenant-Generaal Best Kazerne in Vredepeel, where the Counter-UAS (C-UAS) Test Center is located. The general map of the Luitenant-Generaal Best Kazerne is shown in Fig. 3.5 and its corresponding LCZ map is shown in Fig. 3.6. The area contains buildings in the northwest and a runway stretching from the southwest to the northeast. The LCZ map correspondingly classifies the area with buildings in classes 6 and 9, open and sparsely-built lowrise. The runway area is classified as classes B and D, scattered trees and low plants. The Luitenant-Generaal Best Kazerne is a good representation of the surroundings found in the military operations and the combat scenarios.

It has been demonstrated by the examples above that distinctions can be made among different terrain complexities by employing the LCZ classification. Therefore, the urbanisation and land cover aspects of the environment in defining the scenarios are based on the LCZ classification system. First, two subgroups are defined: built-up and non-built-up areas. For the built-up area, the highly urbanised area containing the LCZ classes of 1-5 is the most challenging scenario. This is, for example, the urban core of Amsterdam. Next, the suburban area containing the LCZ classes 6-10, and occasionally E, are relatively simpler. Examples of this type are industrial areas, ports, and international airports, i.e. the critical infrastructures. Similarly, for non-built-up areas, two subgroups are defined based on the complexity. First, areas that contain sparsely built lowrise buildings and are covered with some vegetation are a relatively more complex type. This is, for example, the north side of the Luitenant-Generaal Best Kazerne. Finally, the most simple scenario is an open area with low plants, containing only the LCZ classes C-F. An example of this area is the south (runway) part of the Luitenant-Generaal Best Kazerne.

The scenario definitions explained above are summarised in Table 3.4. For the urbanisation and land cover aspect of the environment, the difficulty for optics and acoustics are assumed to be identical. The difficulties are also specified in the table.

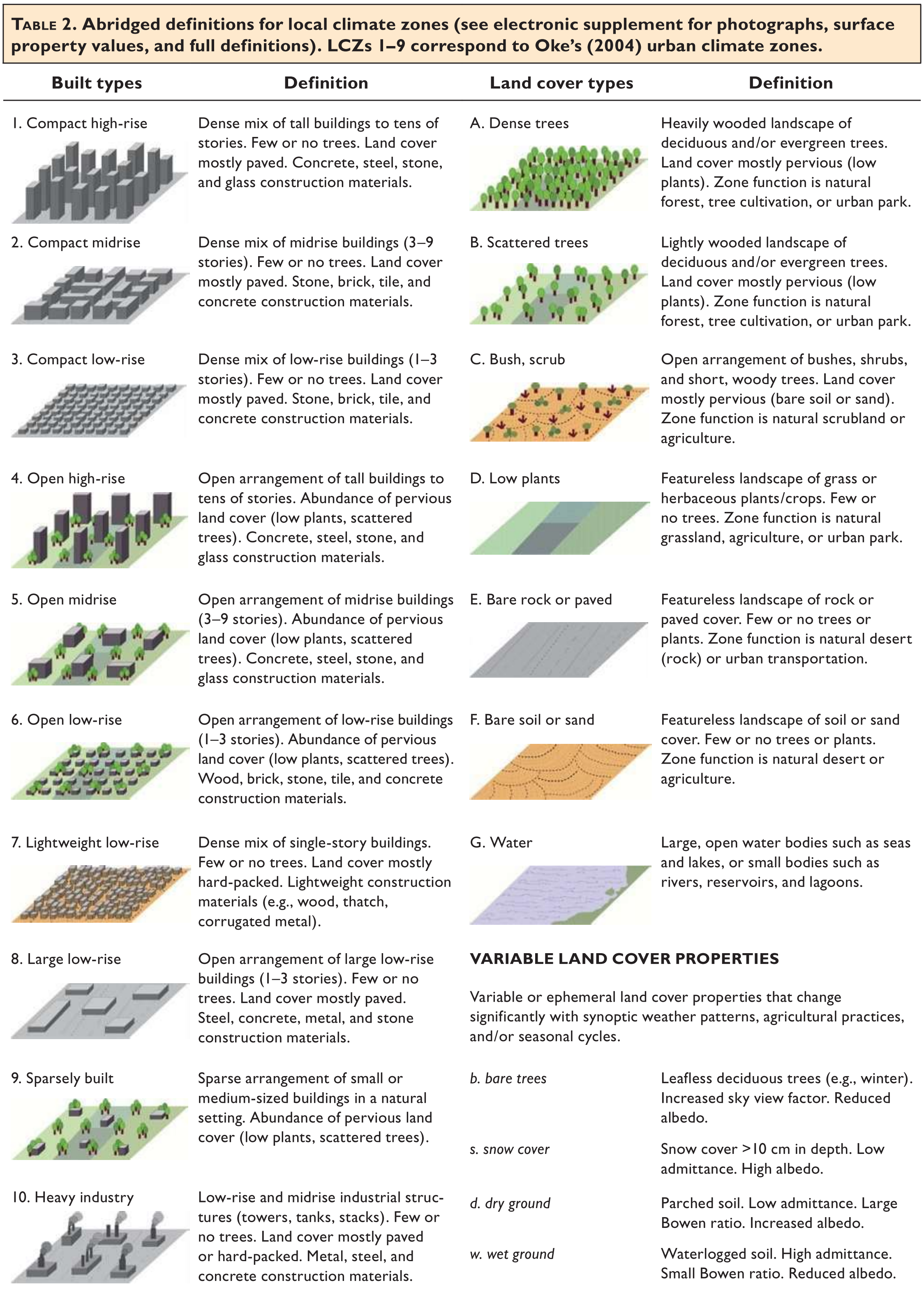


Table 2. Abridged definitions for local climate zones (see electronic supplement for photographs, surface property values, and full definitions). LCZs 1–9 correspond to Oke's (2004) urban climate zones.

Built types	Definition	Land cover types	Definition
1. Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	**VARIABLE LAND COVER PROPERTIES**	Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	*b. bare trees*	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
		s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
10. Heavy industry	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.	*d. dry ground*	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
		w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Figure 3.3: Definitions of the LCZ classes, taken from Steward and Oke [45].

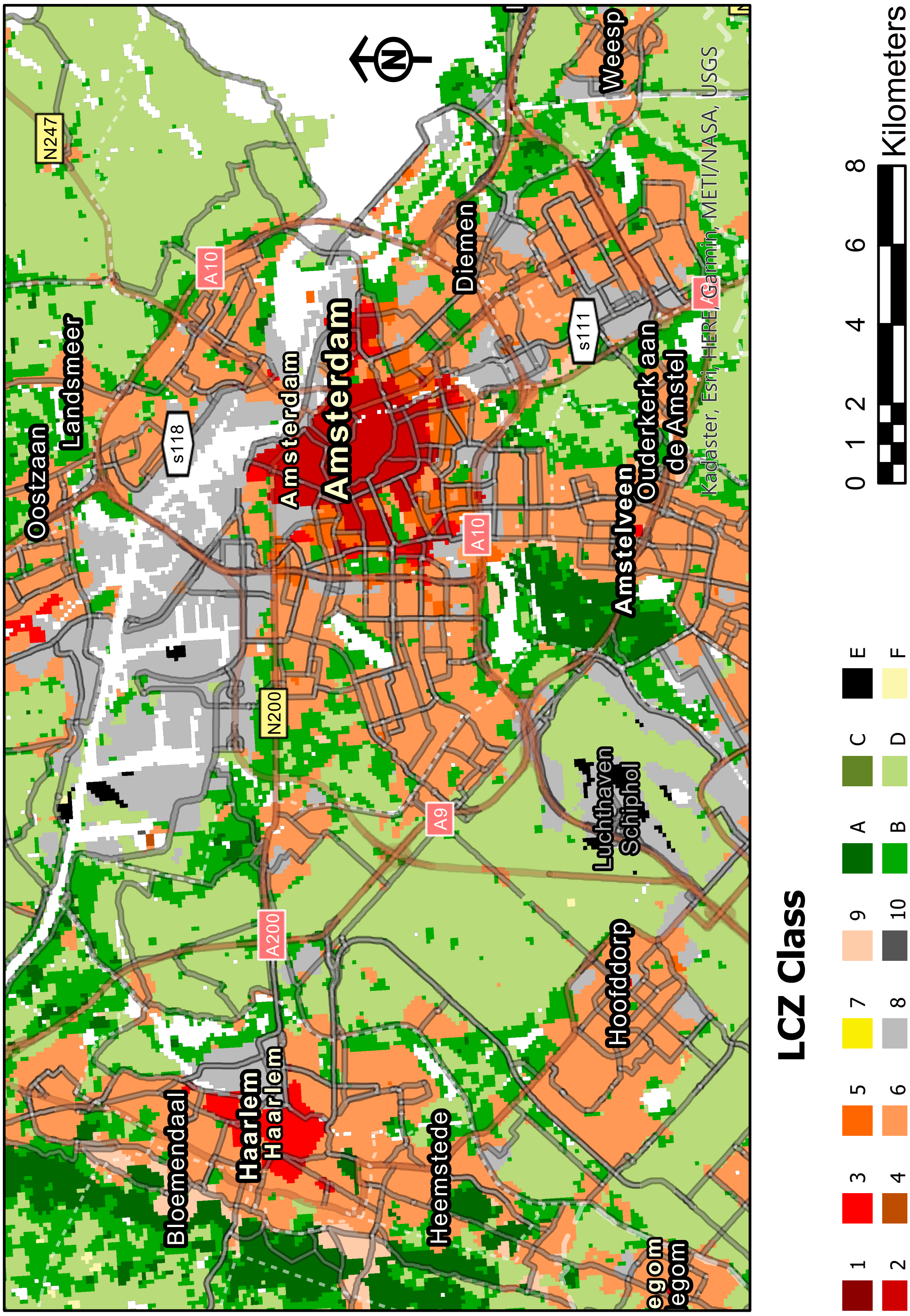


Figure 3.4: LCZ map of Amsterdam and its surroundings.

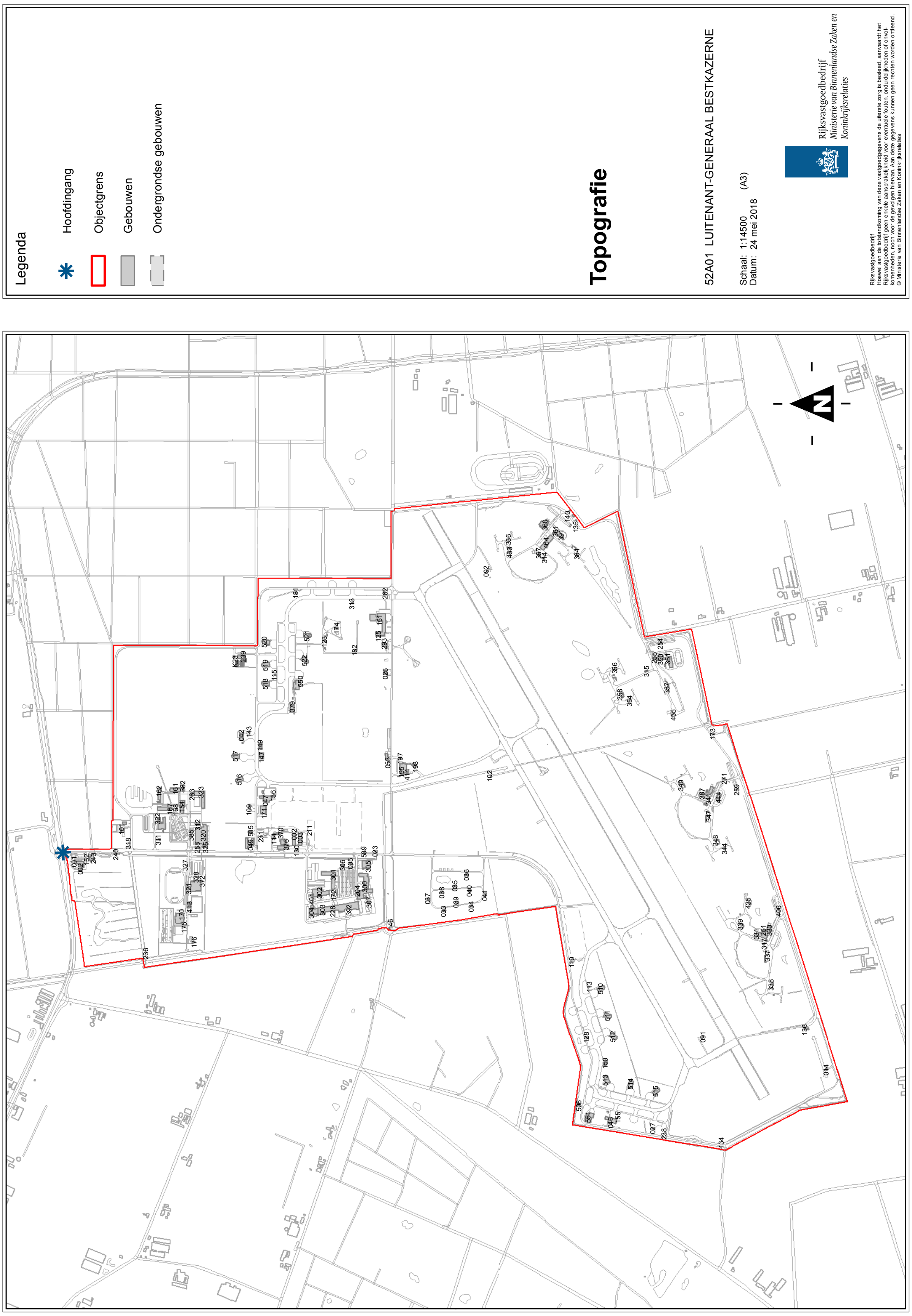


Figure 3.5: Map of the Luitenant-Generaal Best Kazerne.

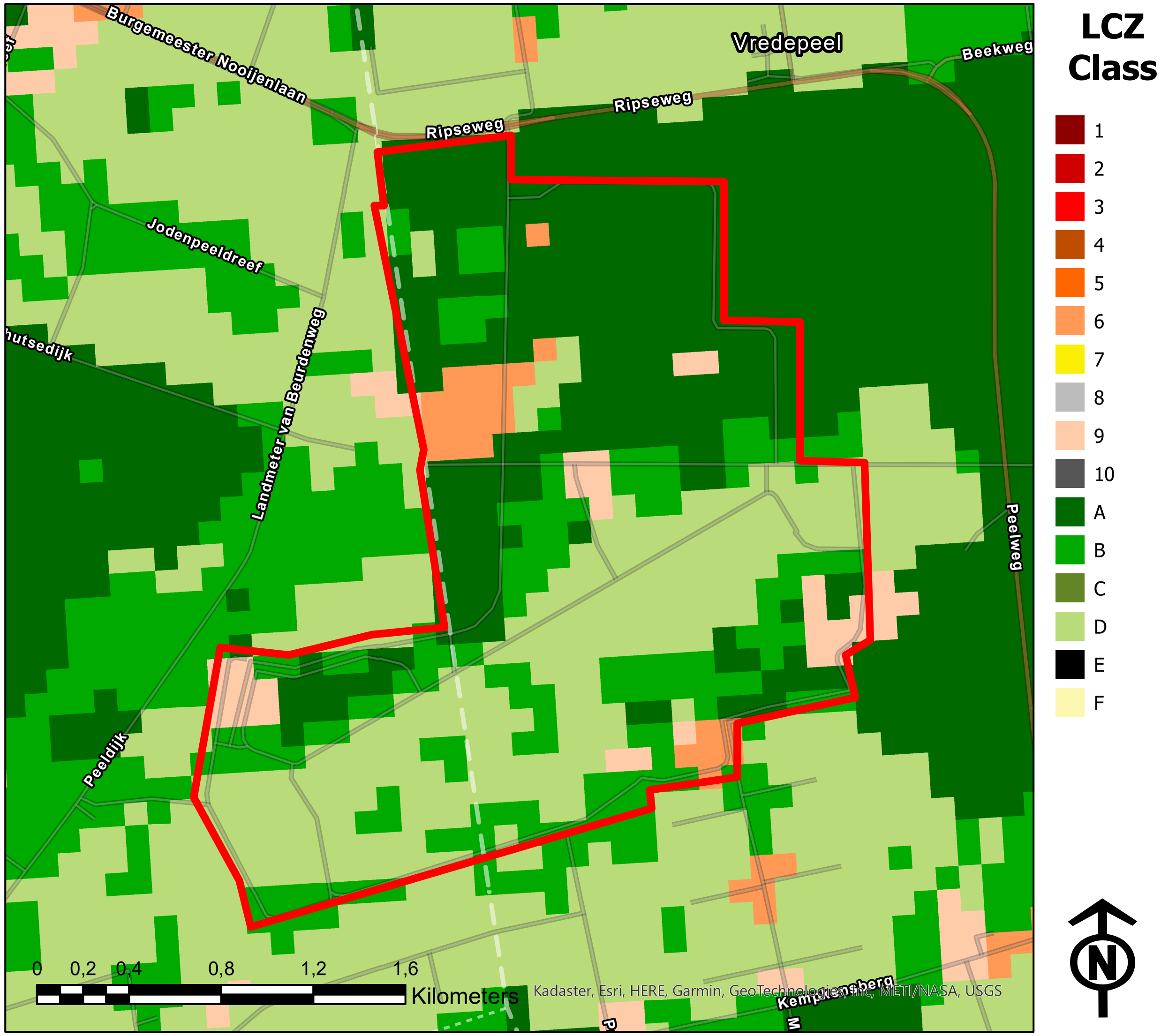


Figure 3.6: LCZ map of the Luitenant-Generaal Best Kazerne. The red line indicates the boundary corresponding to the 'Objectgrens' in Fig. 3.5.

Table 3.4: Urbanisation and land cover schemes for the scenarios

Own Terminology	Difficulty for optics and acoustics	LCZ classes	Examples
Built-up area			
Built-up, complex **U1&C2**	High	1 - 5	Cities, Downtowns
Built-up, simple **U1&C1**	Medium	6 - 10	International airports, Ports, Industrial areas
Non-built-up area			
Non-built-up, complex **U0&C2**	Medium	8, B, E	Airbase, Military base
Non-built-up, simple **U0&C1**	Low	C, D, F	Grass/ crops fields

3.4. Concurring Events

In this consideration, concurring events entail all other events occurring in the environment apart from the UAV operations. These events may interfere with performances of the acoustic and optical sensors for UAV detection. For instance, detecting a UAV flying in a bustling urban environment is indeed more challenging than in a quiet rural grass field.

For acoustic sensors, noise produced by concurring events will impact their UAV detection performances. Table 3.5 from a textbook of Kurra [30] shows a list of possible outdoor noise sources. This is a relevant source for defining the scenarios. However, additional quantitative criteria for their interference with the acoustic detection are needed.

For this purpose, two criteria are used to quantify the degree to which the concurring event interferes with the acoustic detection. First, the Signal-to-Noise Ratio (SNR) of the concurring event is defined as the relative Sound Pressure Level (SPL) between the amplitude of the event SPL time series and the averaged SPL of the noise floor, i.e. when there is no event. A schematic for the SNR calculation is shown in Fig. 3.7a. Nevertheless, for events with identical SNRs, acoustic monitoring for UAV detection is less challenging when the event occurs only intermittently, i.e. not continuously, shown in Fig. 3.7a.. Therefore, another criterion for quantifying the intermittency is incorporated. This criterion is called the Intermittency Ratio (IR). It is originally used for quantifying transportation noise exposure in the work of Wunderli et al. [53] and is defined as

$$\mathrm{IR} \equiv 10^{0.1(L_{\mathrm{eq.},T,\mathrm{Events}} - L_{\mathrm{eq.},T,\mathrm{Total}})} \times 100\%, \tag{3.1}$$

where $L_{\mathrm{eq.},T,\mathrm{Total}}$ is the equivalent SPL of the event averaged over a continuous time span T, or mathematically

$$L_{\mathrm{eq.},T,\mathrm{Total}} \equiv 10\log_{10}\left(\frac{1}{T}\int_0^T 10^{0.1\mathrm{SPL}(t)}\mathrm{d}t\right). \tag{3.2}$$

A threshold K in dB is defined as an SPL with an arbitrary offset C above $L_{\mathrm{eq.},T,\mathrm{Total}}$:

Table 3.5: Summary of outdoor noise sources, taken from Kurra [30].

Generic noise	Specific group	Level/scale	Noise-producing component
Transportation noise	Road traffic	Individual vehicles	Motor vehicles: heavy vehicles (trucks), moderate vehicles (vans), light vehicles (cars) and motorcycles
		System	Traffic and roads (urban, intercity, and motorways)
	Railway traffic	Individual vehicles	Locomotive and wagons passing-by or stop-start at stations
		System	Railway traffic: at grade, elevated or underground and tracks (rails, joints, ballast, sleepers, bridges, etc.), train yards
	Aircraft traffic	Individual vehicles	Aircraft and helicopters, flying over, taking-off or landing
		System	Airport traffic, routes (taxiways, runways, flight paths), ground test zones
	Waterway traffic	Individual vehicles	Waterway vehicles (boats, ships, cargo vessels, etc.) transiting or mooring at quay
		System	Waterway traffic density (number of vessels), ports, harbors, wharfs, and shipyards
Construction noise	Road and building construction	Individual vehicles	Construction equipment, stationary or moving: bulldozer, backhoe, cranes, etc. and operations
		System	Construction site: Number of equipment, operations according to time schedule
Industrial noise	All types of manufacturing processes	Individual sources	Mechanical and electrical equipment and operations
		System	Number and type of equipment in open air or closed premises
Entertainment/ recreational noise	All types	Individual sources	Amplified sound emitters (LS), electronic devices, machines like roller coaster, etc.
		System	Outdoor premises and sports areas
Wind farm noise	All types	Individual sources	Wind turbines and components
		System	Wind farms

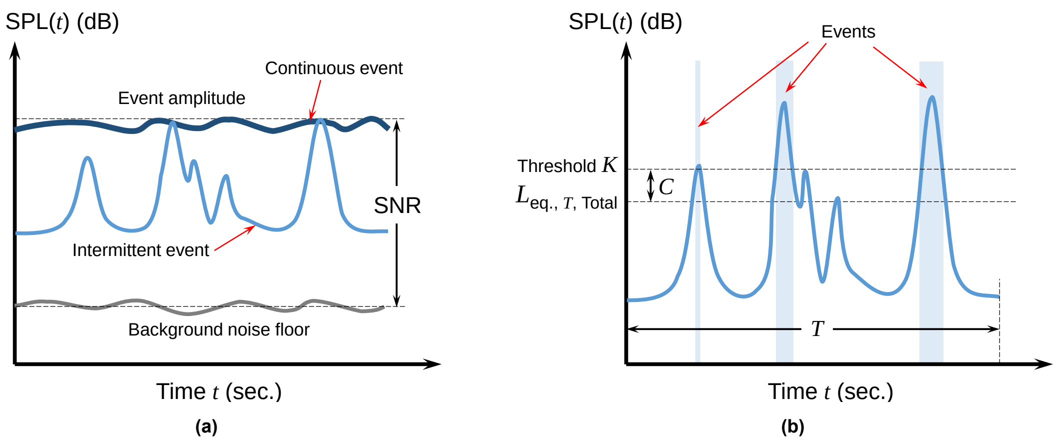


Figure 3.7: (a) Schematic of a continuous event and an intermittent event having the same SNR and (b) Schematic of the event detection for the IR calculation.

$$K \equiv L_{\text{eq.},T,\text{Total}} + C. \tag{3.3}$$

The definitions of K and C are illustrated in Fig. 3.7b. Wunderli et al. suggest to take $C = 3$ dB. Finally, the event-based SPL $L_{\text{eq.},T,\text{Events}}$ is integrated only when SPL(t) exceeds the threshold K, or mathematically,

$$L_{\text{eq.},T,\text{Events}} \equiv 10\log_{10}\left(\frac{1}{T}\int_0^T \mathrm{H}[\mathrm{SPL}(t) - K]10^{0.1\mathrm{SPL}(t)}\mathrm{d}t\right), \tag{3.4}$$

where H[.] is the Heaviside step function.

Table 3.6: Difficulty matrix for acoustic (A) and optical (O) sensors based on concurring event SNR and IR.

Concurring event SNR	**Concurring event IR**		
	Low 0 - 20 %	Medium 20 - 60 %	High 60 - 100 %
Low 0 - 3 dB	A: Low, O: Low **SNR1&IR0** e.g. No concurring event/ event occurring very far away		
Medium 3 - 6 dB	A: Medium, O: Medium **SNR2&IR1** e.g. Operating industrial sites/ wind farms	A: Medium, O: Medium **SNR2&IR2** e.g. Busy roads	A: Low, O: Medium **SNR2&IR3** e.g. Less-busy roads
High >6 dB	A: High, O: Medium **SNR3&IR1** e.g. Outdoor events/ concerts	A: High, O: Medium **SNR3&IR2** e.g. Construction	A: Medium, O: Medium **SNR3&IR3** e.g. Trains, airplanes, gunshots

Having defined the SNR and the IR, a 3×3 difficulty matrix based on the SNR and IR is formulated. This matrix is shown in Table 3.6. The intervals for the SNR is chosen arbitrarily while the intervals for the IR is chosen based on the road-traffic noise examples of Wunderli et al. [53]. Example real-life events are also given in the table. Assignment of the real-life events to the difficulty matrix is based on their expected intermittency SPLs information provided in literature [6, 37].

By considering Table 3.6, it is expected that the concurring event situation in the urban scenario will belong to the 'SNR3&IR1' type, where the background noise is relatively high and not intermittent. On the other hand, the critical infrastructure such as an international airport, is likely to contain the 'SNR3&IR3' type, because although the aircraft noise is expected to be loud, it occurs intermittently, i.e. only when there is aircraft movement. The military operations scenarios are likely to contain the concurring events other than the ones that have been mentioned. Finally, the combat scenarios are likely to contain the 'SNR3' situation, with varying IRs.

4 Available Sensors

The Counter-UAS Test Center does not own many sensors themselves. The main purpose of this department to investigate which sensors would be suitable for UAS detection and mitigation and therefore does not buy many sensors. They usually borrow them from companies for tests or demos. Furthermore, they support research projects such as ACTION. However, they do have some sensors available and one multi-sensor system will be available next year. Another group of sensors that could be of interest for the ACTION project are the noise and operations monitoring systems (geluidsmeetnetten) placed around military airbase Gilze-Rijen, Leeuwarden and Volkel. All sensors are briefly discussed in this chapter. It should be noted that for now the available sensors will not be taken into account for the scenarios drafted in Chapter 5, as the primary focus of the ACTION project is to detect drones using acoustics and optics. This chapter is created to be aware of the available sensor suite which will only be relevant at later phases of the project.

4.1. DISCUS

DISCUS stands for Deployable Integrated Sensors for Compound Security and is an area protection system designed by Thales. This system consists of radar and optical sensors. The radar component is the Squire radar of Thales. This is a man-portable radar system for medium-range ground surveillance, which can detect and classify targets both on the ground or close to the ground up to 48 km range [49]. Although this system was already designed in 2003, it is able to detect drones and distinguish them from birds due to new software updates. The optical sensor is the FLIR Ranger HDC MS. This system is a combination of an infrared camera and daylight cameras, which can be used for detection at ranges up to 15 km. All cameras are mounted to a pan and tilt mechanism [19].

This system can be used in many scenarios where the proposed ACTION system could work as well and its working mechanism has proven itself in the past as detection system for intruding aircraft. The advantage is its large detection range, however it should be noted that this will be (much) lower than the stated 15 km for drones that fall within this research due to their small size and therefore small radar cross section. Furthermore, the downside of this system is that radar is an active system, as it needs to send out a signal. This can be detected by the drone operator, which is undesirable. Therefore, a passive acoustic detection system will be favourable for military operations. Although the DISCUS system might be able to outperform an acoustic detection system in terms of distance, the passive behaviour of an acoustic system as well as its relative low cost are two of its main advantages.

4.2. Wingman

Wingman is a small portable radio frequency (RF) detection system, designed by the Danish company MyDefence, which creates Counter-UAS systems. Due to its small size and low weight it can be carried easily by the operator on its torso, attached to the clothes. The system works autonomously and is able to warn the operator by sound, vibration or light in case of a detection. The device cannot provide a direction where the UAV is flying. The detection range is a few 100 m, up to 1 km [34].

The Wingman detection system can only work in case of a drone that is operated manually, as it detects the communication link between the vehicle and its ground station. Beside this, its detection range is low compared to e.g. radar systems. However, due to its low weight it will be a useful system during military operations, although it will never ensure that there is no (autonomous) drone flying nearby. Lastly, as it also cannot provide details about the direction of the UAV, in other scenarios acoustic and optical sensors would be preferred.

4.3. Sorama Listener 64

The Counter-UAS Test Center already owns an acoustic system: the Sorama Listener 64. This is a small box containing 64 MEMS microphones. In total, four microphone arrays are available, where one can be equipped with a camera. This acoustic system is designed to monitor noise pollution in cities. Using smart algorithms, it can identify the sound level and the source of the sound [44]. However, due to its design it is not capable of correctly identifying sound sources like drones, and therefore it is unsuitable for drone detection. According to the C-UAS Test Center, the system showed inconsistent results and had a low detection range.

4.4. Multi-Sensor System

Next year (2023), a new multi-sensor system will arrive, consisting of seven different sensors. This is an interesting system for possible data fusion with the data obtained with sensors for the ACTION project. However, as the C-UAS Test Center is still in the procurement process, no details are known yet, except that the system will at least contain an RF sensor, radar and an EO camera.

4.5. Geluidsnetten

Next to the detection sensors that are available at the C-UAS Test Center, another sensor suite must be explored to see if it can be incorporated in the ACTION project. These are the noise and operations monitoring systems, which is better known as *geluidsnetten* in Dutch. These systems are located around the three military airports Gilze-Rijen, Leeuwarden and Volkel, to monitor the noise contours nearby the airport. It is placed at these locations to provide information to the local residents on the sound pressure levels. The locations of these microphones are therefore determined in collaboration with the residents and beside the fixed microphones one or two mobile microphones are available for each airport to measure the sound pressure level at any other desired location. A nearly real-time flight and noise tracker is available online, where the A-weighted sound pressure level are shown for each microphone.

The monitoring system is a design by Casper, which is a company providing noise and monitoring solutions world-wide to a large variety of customers in the aviation industry. The microphones they use for monitoring are the Cirrus CR:465 Galactus Noise Monitors. Currently, the system outputs the A-weighted equivalent sound level $L_{A,eq}$ for both the octave and 1/3-octave bands, with a 5-second delay. If desired other outputs can be obtained as well, but this should be done in collaboration with Casper to change the settings of the system. However, they are limited to the available acoustic measurement values of the previously mentioned microphone and according to the datasheet, pressure-time is not one of them [38]. This makes the noise and operations monitoring system less interesting to use directly for detection and localisation, as this is not possible with only sound pressure levels. However, indirect use of the system should be investigated, such as including the flight radar and noise measurements to check if a detected sound could come from an aircraft, to lower false positives and negatives.

5 Scenario Exploration

After elaborating on the characteristics of the two relevant components for the scenarios, the opportunities and constraints for both components in relation to the different scenarios can be explored.

5.1. Unmanned Aerial Vehicles

In Chapter 2, a variety of characteristics of UAVs is provided. Using these characteristics, it is possible to create a design option tree to explore the possibilities for different scenarios. However, it is also relevant to look beyond the characteristics of the vehicles only, as it is not straightforward to make assumptions on what kind of UAVs will be present during different scenarios. This section will therefore not only provide the design options regarding the UAVs, but also a description of the relevance of this exploration for the scenarios.

5.1.1. Design Option Tree

As can be read in Chapter 2, there are six different UAV characteristics relevant for this project, and all characteristics have subcategories. This can be summarised in a design option tree as shown in Fig. 5.1. As can be seen from this tree, a large amount of combinations is possible. Before looking into which combinations are relevant for different scenarios, it is helpful to investigate what types of drones are actually available for testing. For this, a list per category and subcategory is created with the amount of drones that fall within this group, as shown in Table 5.1. It should be noted that not all available drones at the faculty of aerospace engineering are mentioned here, as some are custom-made and not all details are known. However, the majority of these vehicles are fixed-wing UAVs that fall within the micro category. Furthermore, the engine powered UAV does not fall within the scope of the ACTION project, as it has a mass of 24.9 kg. It is therefore not included in this table for the other categories. However, it is still useful to perform tests with this vehicle, as it is the only way to obtain a sound signature of an engine powered UAV, which will be useful in the database of sound signatures that must be created.

What becomes clear from this table is that the Counter-UAS Test Center does not have a large variety of drones. For all categories, at least 75% belongs to one subcategory. The vehicles from the faculty can fill some of the gaps, although for some categories they cannot offer a large variety of vehicles. It is worth noting that for all subcategories drones are available which means that it is possible to get all desired sound signatures. However, due to the spread of the vehicles among two parties, it is likely that measurement campaigns need to be performed at both the Luitenant-Generaal Best Kazerne and the former airbase in Valkenburg.

Last of all, it is necessary to look back at the different combinations. Some options are not realistic or feasible. Examples of these are engine powered nano drones or hovering fixed-wing UAVs. However, even after a feasibility study, a large amount of options would remain. Above this, when looking beyond realistic combinations, another aspect that must be determined is during what kind of scenarios these combinations would fly. This is however not a straightforward process, as it would lead to assumptions

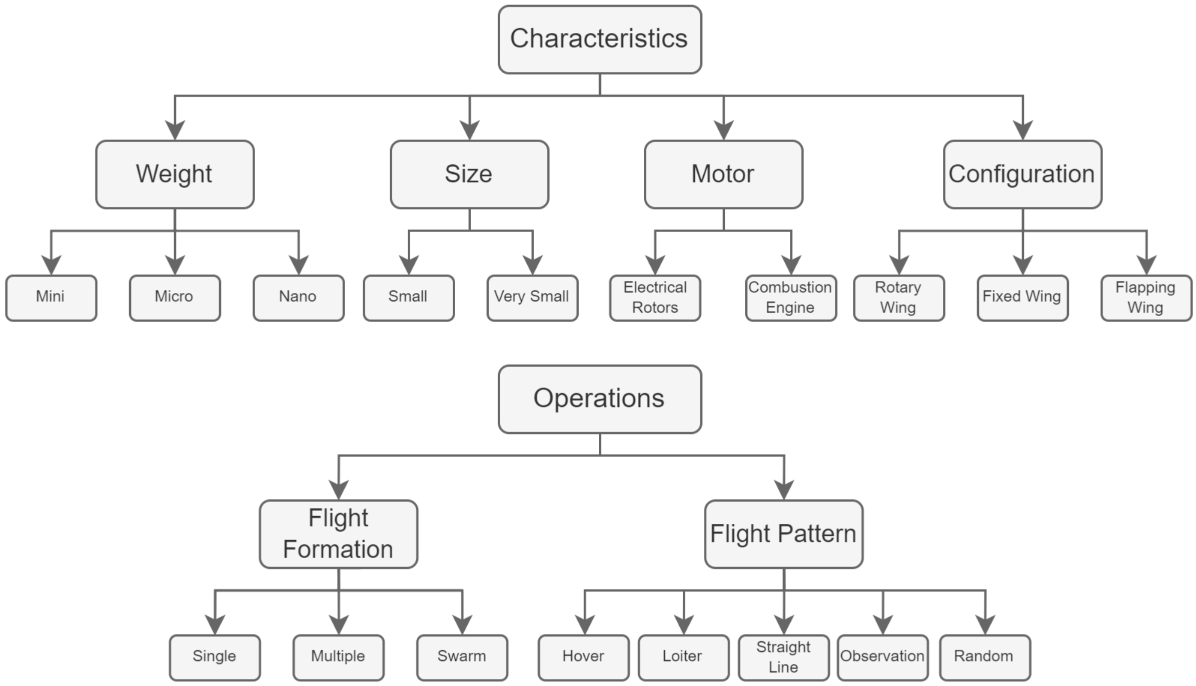


Figure 5.1: Design option tree for the UAV options.

Table 5.1: Amount of UAVs for each category. *The engine powered UAV falls outside the scope of this project due to its weight and is only taken into account for the power category.

Characteristics	Divisions	C-UAS Test Center	Faculty of AE
Weight	Mini	1	1
	Micro	7	8
	Nano	0	2
Size	Small	2	6
	Very Small	6	5
Configuration	Rotary Wing	7	6
	Fixed Wing	1	4
	Flapping Wing	0	1
Motor	Electric	8	11
	Engine	0	1*

that are not necessarily true.

As mentioned in Chapter 2, some combinations are more likely to happen during specific scenarios. A rotary-wing UAV will form a threat mainly in urban environments, during event like Kingsday, or for military operations like the protection of a military base. Fixed-wing UAVs are more likely to be encountered during combat scenarios which involve attacks or reconnaissance at large distances from the UAV ground control station. However, this does not mean that fixed-wing UAVs will never be used to observe a military airbase or that there will never be an encounter with a rotary vehicle during a military operation. It is therefore not sensible to rule out vehicles for a specific scenario. Above this, as the expected approach for the ACTION project is to build one database of sound signatures on which the detection system relies on, it is not necessary to specify categories of UAVs for the scenarios.

5.2. Environment Scenarios

Having defined the components of the environment in Chapter 3, this chapter formulates the environment scenarios by exploring all possible combinations of the components. The options for each component are summarised in Fig. 5.2. Each option is represented by a short nomenclature. The nomenclatures and quantitative details for all of the options have been elaborated upon in Chapter 3. In summary, there are 5 options for the visibility, 3 options for the wind speed, 3 options for the daylight conditions, 4 options for the urbanisation and land cover, and 7 options for the concurring event. Therefore, when combining every component, there will be $5 \times 3 \times 3 \times 4 \times 7 = 1,260$ possible environment scenarios.

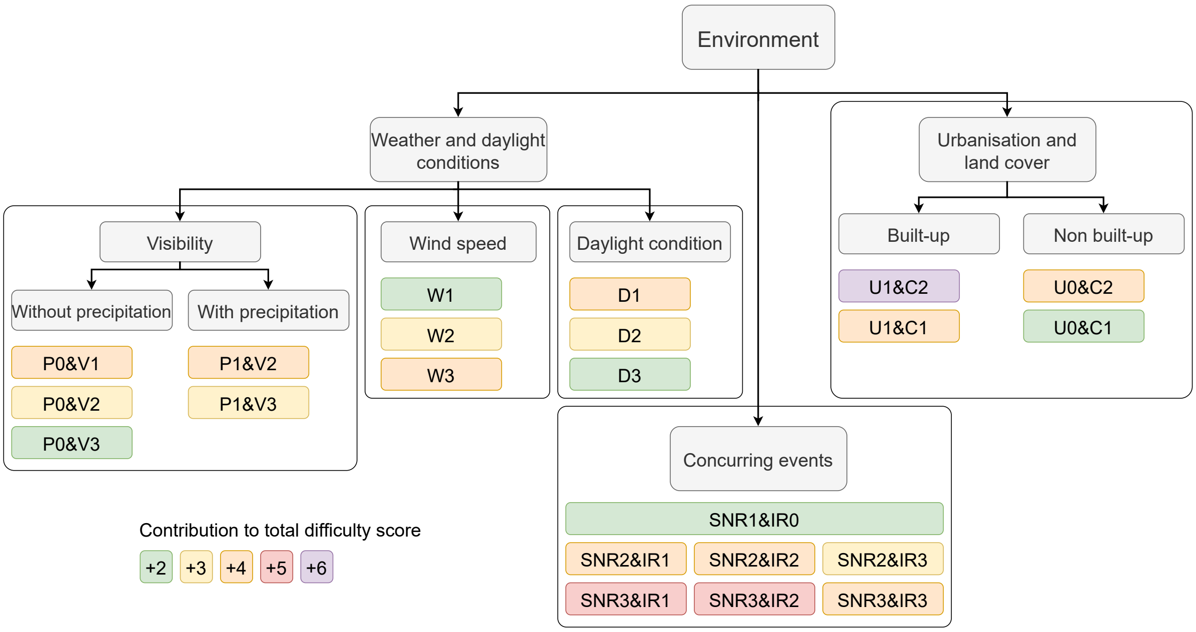


Figure 5.2: Options for formulating the environment scenarios.

In Chapter 3, difficulty levels of each option were assigned for acoustic and optical sensors. In this chapter, corresponding difficulty scores from 1 to 3 are further allocated. The scores of 1, 2, and 3 correspond to low, medium, and high difficulties, respectively. When combining the components into a scenario, their scores are added up to calculate the *total difficulty score*. Each option's contribution to the total difficulty score is specified in Fig. 5.2. Subsequently, the 1,260 scenarios are ranked with respect to their total difficulty scores.

A plot visualising the environment scenarios ranked based on their total difficulty scores, i.e. acoustics plus optics, is shown in Fig. 5.3. Individual difficulty scores for acoustics and optics are also visualised. A MATLAB package for generating an interactive version of this plot is available. It can be seen that the total difficulty score ranges from 10 to 23, and most scenarios fall within the total difficulty score range of 15 to 19. This is confirmed by the histogram in Fig. 5.4.

The scenario with the lowest difficulty score can be articulated by combining the corresponding descriptions provided in the tables in Chapter 3, resulting in

> *Daytime, high visibility, low wind, on a grass/ crops field, no concurring event*

while there are 4 most difficult scenarios, which are, in general:

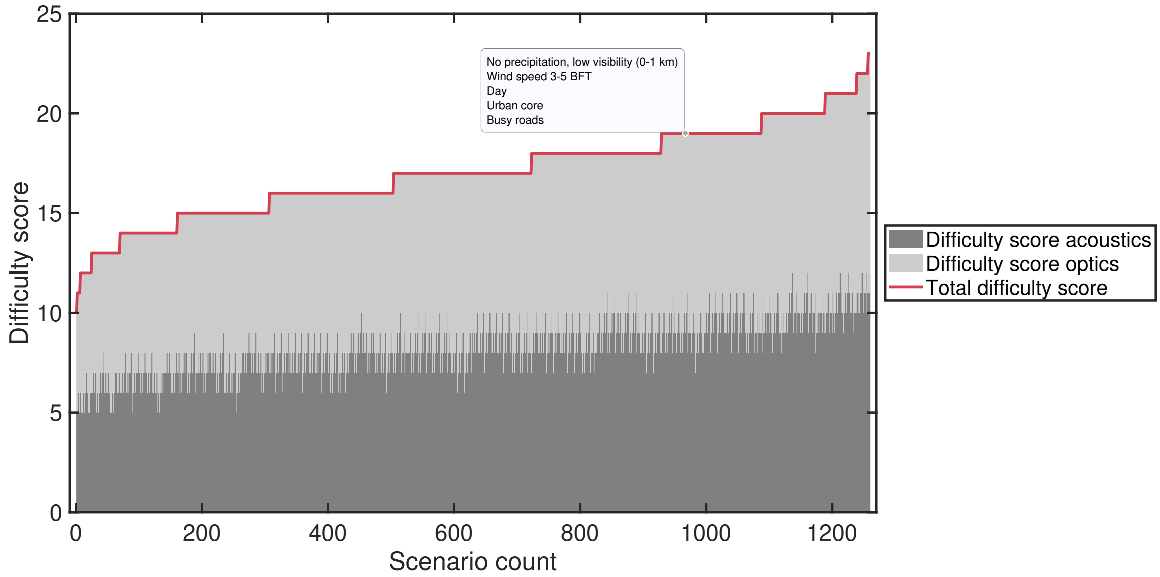


Figure 5.3: Environment scenarios ranked by their total difficulty scores.

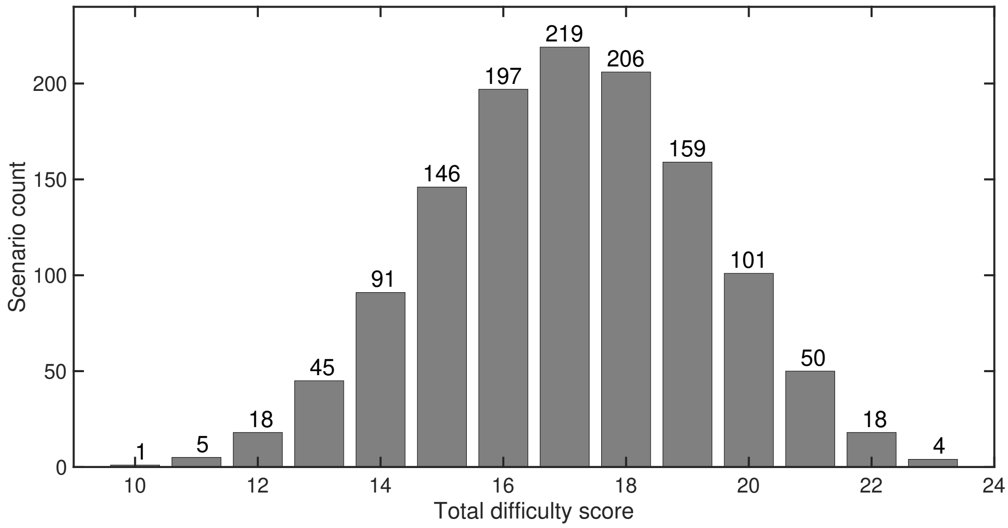


Figure 5.4: Histogram showing the number of scenarios for every total difficulty score.

Nighttime, low to medium visibility, high wind, in an urban core, and an outdoor event or construction is taking place

The scenarios presented above represent the two extremes. The scenario with the lowest difficulty score may be too ideal for testing performance of the UAV detection system. However, it is a perfect scenario for collecting acoustic and optical data of UAVs in order to create a data library, i.e. training. On the other hand, the most difficult scenarios may also be too unlikely to occur in reality, e.g. outdoor events in the urban scenario are not likely to take place during extreme weather conditions. The scenarios with the highest total difficulty score are therefore neglected.

For the practical implementation, it is important to keep in mind that, although the location and time can be selected for testing the UAV detection system, some components in the scenarios such as weather conditions are not fully under control. Therefore, instead of opting for unique scenario definitions, it is motivated to define three *scenario difficulty classes* that contain a broad variety of possible scenarios as shown in Fig. 5.5. These classes are used to guide the location and time selection for the tests while giving some flexibility to the components that are not fully under control. There also exist *training scenarios* which do not fall within these classes, but are interesting for training data collection. The first measurement campaigns will be done in these training scenarios to develop a data library. As the project progresses, testing, and probably additional training data collection, will be carried out in scenarios ranging from the lowest to the highest difficulty class. This classification system allows flexibility for the scenario while still systematically ensuring that the difficulty level builds up along with the project timeline. Therefore, it is of ultimate aim to cover testings for at least several scenarios in every difficulty class by the end of the ACTION project.

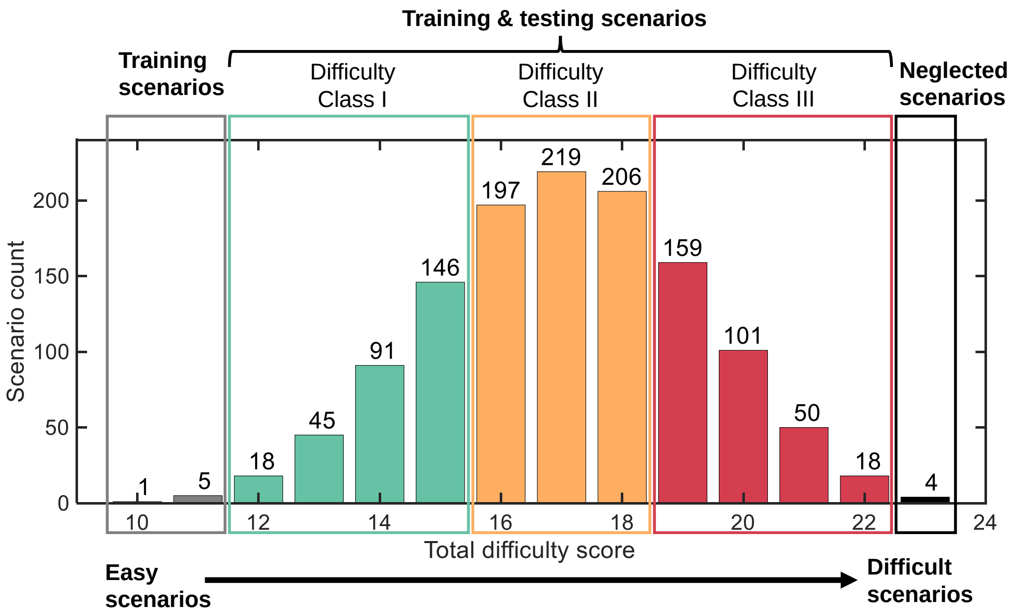


Figure 5.5: Scenario classifications.

Having defined the difficulty classes, a guideline for designing a measurement campaign corresponding to scenarios in every difficulty class is made. This is illustrated in Table 5.2. The table shows the difficulty classes and maximum possible total difficulty scores of certain environment scenarios, if the most difficult option of each environmental aspect is added cumulatively. The difficulty increases towards the lower rows and the right columns. The first row assumes that only the urbanisation and land cover vary while the other components of the environment are the ones with the lowest difficulty scores, i.e. ideal scenarios. The urbanisation and land cover are considered first because the selection of which is fully under control.

The table suggests that the training scenarios shall be done on a grass/crops field with ideal weather conditions and little-to-none background noise. Difficulty can be added by either moving to a more urbanised environment (move to the right side) or increasing the difficulty of other aspects (move down), such as testing during nighttime. Each lower row of the table assumes that one environmental component is replaced by an option with the highest difficulty score. The lower the row, the more difficult to control that environmental component during the measurement campaign, i.e. controlling the time of the day is easier than controlling the weather conditions during the measurement. This table helps to guide the measurement campaign planning, such as selection of measurement sites and time, so that the most diverse difficulty classes are covered.

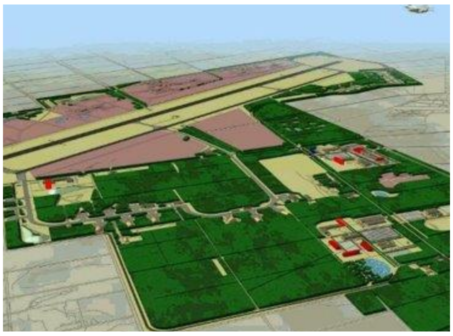
Table 5.2: Maximum possible difficulty classes for each urbanisation and land cover option with adding difficulties from other environmental components.

Scenario nomenclatures	Scenario explanations	Cumulated difficulty scores	Non built-up		Built-up	
			U0&C1 Grass/ crops fields +2	U0&C2 Air fields/ military base +4	U1&C1 Industrial areas, international (air)ports +4	U1&C2 Cities, downtowns +6
D3-SNR1&IR0-W1-P0&V3	Daytime, no concurring event, low wind, no precipitation and good visibility	+8	**Training scenarios (10)**	**Class I (12)**	**Class I (12)**	**Class I (14)**
D1	Night time	+2	**Class I (12)**	**Class I (14)**	**Class I (14)**	**Class II (16)**
SNR3&IR1 or SNR3&IR2	Noisy and non-intermittent concurring events	+3	**Class I (15)**	**Class II (17)**	**Class II (17)**	**Class III (19)**
W3	High wind	+2	**Class II (17)**	**Class III (19)**	**Class III (19)**	**Class III (21)**
P0&V1 or P1&V2	Reduced visibility (due to precipitation)	+2	**Class III (19)**	**Class III (21)**	**Class III (21)**	**Neglected scenarios (23)**

Scenario classifications (Maximum total difficulty score)

5.3. Outlook to Realistic Situations

This section relates real-life situations to the defined scenarios, their difficulty classes, and their types (referring to Table 1.1). The following real-life situations has been defined by the C-UAS Test Center and are briefly summarised below.



- **Military airfield**: This describes protection of a military airfield from ill-intent or spying UAVs from enemies or terrorists that disrupt or aim at attacking military operations. This situation belongs to the **Military operations** scenario type, and possibly the **Combat** scenario type.

- **Port of Rotterdam**: This describes protection of a large industrial area from UAVs that could cause damages or interruptions. This situation belongs to the **Critical infrastructure** scenario type.

- **Schiphol Airport**: This describes protection of an international airport. Short UAV disruptions of air-traffic operations will result in large monetary losses. There are, in average, 40 aircraft movements per hour which could make intermittent noise. This situation also belongs to the **Critical infrastructure** scenario type, where the background noise levels are likely to be higher and more intermittent than the Port of Rotterdam situation.

- **Prinsengrachtconcert**: This describes protection of a large-scale concert event in an urban area. This is an outdoor and noisy event with crowds, and possibly famous persons such as a royal family member are present. This situation belongs to the **Urban** scenario type.

Based on their descriptions, the situations above can be associated with the scenarios formulated in Table 5.2. Next, their corresponding possible difficulty classes (depending on other environmental conditions) can be determined, detailed in Fig. 5.6. These situations are also associated to the scenario types presented in Table 1.1 in Chapter 1. The systematic difficulty classes and their strict definitions provide a sequential guideline for the measurement campaign site selection, where the difficulty gradually increases. The guideline suggests starting from the military airfield. Next, difficulty is increased when moving towards a large-scale industrial area and/or an international airport. Finally, testing in an urbanised environment, especially during a large-scale public event, is the most difficult situation. Therefore, the scenario type difficulty ranking is as follows: (from low to high difficulty) Military operations, Combat, Critical infrastructure, and Urban. This outcome is utilised in further measurement campaign planning presented in Chapter 6.

Military airfield

Prinsengrachtconcert

Scenario nomenclatures	Scenario explanations	Cumulated difficulty scores	Non built-up: U0&C1 Grass/ crops fields +2	Non built-up: U0&C2 Air fields/ military base +4	Built-up: U1&C1 Industrial areas, international (air)ports +4	Built-up: U1&C2 Cities, downtowns +6
D3-SNR1&IR0-W1-P0&V3	Daytime, no concurring event, low wind, no precipitation and good visibility	+8	Training scenarios (10)	Class I (12)	Class I (12)	Class I (14)
D1	Night time	+2	Class I (12)	Class I (14)	Class I (14)	Class II (16)
SNR3&IR1 or SNR3&IR2	Noisy and non-intermittent concurring events	+3	Class I (15)	Class II (17)	Class II (17)	Class III (19)
W3	High wind	+2	Class II (17)	Class III (19)	Class III (19)	Class III (21)
P0&V1 or P1&V2	Reduced visibility (due to precipitation)	+2	Class III (19)	Class III (21)	Class III (21)	Neglected scenarios (23)

Scenario classifications
(Maximum total difficulty score)

Port of Rotterdam

Schiphol airport

Figure 5.6: Possible difficulty classes for the real-life scenarios.

6 Planning

6.1. Measurement Campaigns

The final scenario classification as described in Chapter 5, and in particular Fig. 5.5 and Table 5.2, are used to create a first version planning of the measurement campaigns throughout the project including their expected goals, i.e. reaching certain difficulty levels. Therefore, the goals can be set in terms of difficulty level regarding the environmental components. During all measurement campaigns, a large variety of UAVs in terms of their characteristics as described in Chapter 2, should be flown to obtain as much acoustic and optical data as possible. The aim is to create a large data library of many drones that are operating in different environmental settings for developing the detection, classification, and identification algorithms in the subsequent stages of the ACTION project.

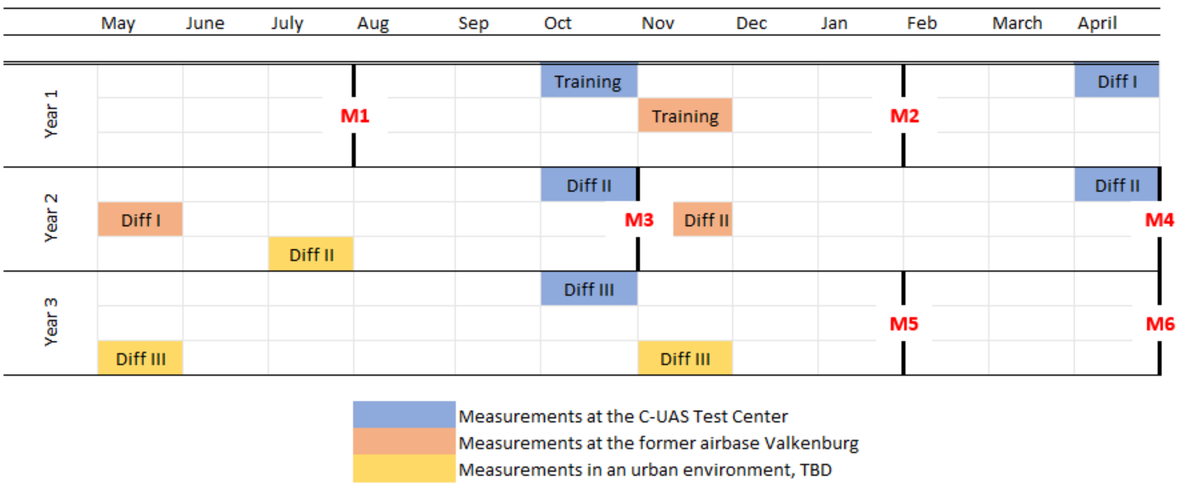


Figure 6.1: Planning of the measurement campaigns and milestones of the ACTION project, with 'MX' indicating the milestones and 'Diff X' indicating the difficulty class to reach.

The first version planning is shown in Fig. 6.1 and the milestones that are mentioned in this planning are described in Table 6.1. The milestones are in accordance with the ACTION project proposal. It should be noted that milestone 2 up to and including 6 are *demonstrations*, which will also take place at one of the measurement locations. The demonstrations are differentiated from the measurement campaigns because they are not meant for data collection. Therefore, unlike the measurement campaigns, only a selection of the UAVs will be flown during the demonstrations. Only the ones that are relevant for a specific scenario type of interest, such as the urban scenario in milestone 5, will be flown. These demonstrations are purely for tracking the ACTION project progress. In the planning, the objective of the measurement campaigns is mentioned in terms of difficulty level, which are detailed in Fig. 5.5. To

Table 6.1: Descriptions of the milestones mentioned in the planning.

Milestone	Description	Work Packages (WP)
M1	Scenarios	WP 1 Done
M2	Acoustic & Optical Sensor Demo	-
M3	Detection & Localisation Demo	-
M4	Classification & Identification Demo	WP 3 Done
M5	Urban Environment Demo	-
M6	Final Demonstration	WP 2, 4, 5, 6, 7 Done

obtain as much data as possible in different environmental conditions, many drone types will be flown during each campaign.

It is currently expected that there will be three measurement locations: the C-UAS Test Center, the former airbase Valkenburg and an urban environment of which its exact location will be specified at a later stage of the project, depending on the needs regarding the urban and land cover element explained in Chapter 3. At the first location, UAVs of the C-UAS Test Center can be tested and at the second location UAVs of the faculty of Aerospace Engineering can be tested. Most of the time, measurements at both locations are planned right after each other and they do have the same objective. The objective is defined in terms of difficulty level which are specified in Chapter 5. The reason to put the measurements close to each other is to be able to gather a lot of different data in a short period of time belonging to the same difficulty level, such that after that a few months of processing time can be planned to create and improve the detection algorithm. Towards the end of the project, the measurement campaigns at the former airbase of Valkenburg will be replaced by measurements in an urban environment, to ensure that the difficulty level during the experiments can be increased.

For exact determination of the conditions that must be tested, Table 5.2 should be consulted. This table shows what environmental element or elements should be altered and how this should be done in order to obtain a desired difficulty level given a location.

6.2. Continuous Data Collection

The major concern regarding correct detection and localisation through advanced approaches like machine learning is the amount of training data. To train an algorithm sufficiently, a large training set is required. If it turs out that not sufficient (varied) data can be obtained during the dedicated measurement campaigns, it can be useful to look into a more continuous data collection method in between the measurement campaigns. Options for this are leaving a measurement system at the Counter-UAS Test Center which can be operated easily every time test flights are made, doing something similar for the (almost) weakly measurements at the former airbase of Valkenburg or cooperate with companies that produce and exploit drones in a variety of applications. One example company that would be interested in such a cooperation is Mapture [31]. It should be noted that the implementation of this plan depends on the development of the project and sensor systems throughout the project and should be worked out in more detail to ensure correct data collection while not bothering operators too much.

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A

Estimating Maximum UAV Detection Distance for Optical Sensors

Under ideal visibility condition, Detection, Identification, and Recognition (DRI) of targets, i.e. UAVs, by optical sensors depend on the number of pixels the target occupies on the resulting image. Standard DRI requirements [8, 26] are shown in Fig. A.1.

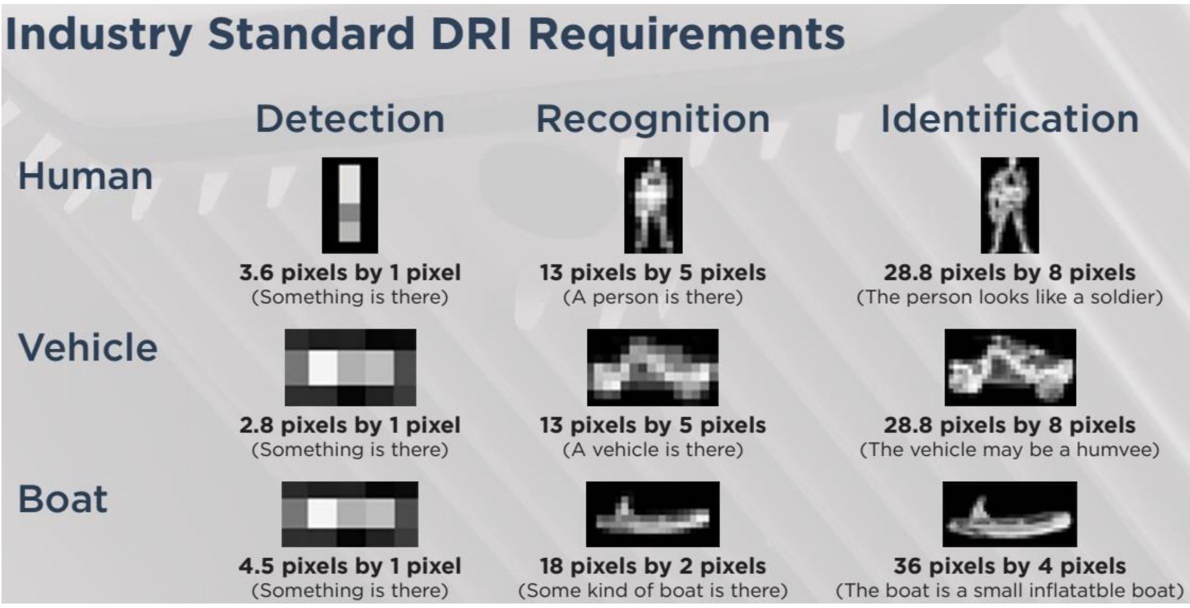

Figure A.1: DRI requirement for target detection, taken from [26].

For the ACTION project, it is of interest to estimate the maximum sensor-to-target distance D_{D} for the optical detection of UAVs. This distance depends on the size of the UAV L_{UAV}, the pixel requirement for the detection $\text{px.}_{\text{D,req.}}$, the resolution in pixels of the camera $\text{px.}_{\text{cam.}}$, and the angular Field Of View (FOV) θ_{FOV} [47]. It is noteworthy that θ_{FOV} varies inversely with the focal length, i.e. the optical zoom. Assuming that the UAV is in the middle of the FOV, the distance D_{D} is estimated as follows:

$$D_{\text{D}} = [0.5 \times L_{\text{UAV}} \times \text{px.}_{\text{cam.}} \div \text{px.}_{\text{D,req.}}] \div \tan(\theta_{\text{FOV}}/2). \tag{A.1}$$

An example calculation is given in the following.

Example Estimate the maximum distance for detecting a UAV having with a size of 0.4 m using a camera with an angular field of view of 24° and a resolution of 512 pixels. Assuming that the UAV is required to occupy at least 5 pixels in order to be detected and there is no optical zoom incorporated.
Solution: from Eq. (A.1)*,*

$$\begin{aligned} D_{\mathrm{D}} &= [0.5 \times L_{\mathrm{UAV}} \times \mathrm{px.}_{\mathrm{cam.}} \div \mathrm{px.}_{\mathrm{D,req.}}] \div \tan(\theta_{\mathrm{FOV}}/2) \\ &= [0.5 \times 0.4\ \mathrm{m} \times 512\ \mathrm{pixels} \div 5\ \mathrm{pixels}] \div \tan[24^\circ \times \pi\ \mathrm{rad}/(2 \times 180^\circ)] \\ &= 96.4\ \mathrm{m} \end{aligned}$$

Therefore, the maximum distance for detecting this UAV is 96.4 m.