NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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STO TECHNICAL REPORT **TR-MSG-154**

Low, Slow, Small Threats Modelling and Simulation

(Modélisation et simulation des menaces faibles, lentes et légères)

This report describes the outcomes of the activity performed during the study.

Published November 2021

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Table of Contents

List of Figures

List of Tables

List of Acronyms

ABS	Acrylonitrile butadiene styrene
AGL	Above the Ground Level
AVT	Applied Vehicle Technology (STO Panel)
BLOS	Beyond Line Of Sight
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
C-LSS	Counter LSS
DEW	Direct Energy Weapon
DIS	Distributed Interactive Simulation
FPV	First-Person View
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HALE	High Altitude Long Endurance
HLA	High Level Architecture
ICAO	International Civil Aviation Organization
IED	Improvised Explosive Device
INS	Inertial Navigation System
ISR	Intelligence, Surveillance and Reconnaissance
LEAP	Leading Edge Aviation Propulsion
LSS	Low, Slow, and Small
LWIR	Long Wave Infra Red
MALE	Medium Altitude Long Endurance
MSG	Modelling and Simulation Group
MWIR	Medium Wave Infra Red
MWTO	Maximum Weight at Take Off
NCTI	Non-Cooperative Target Identification
NED	North-East-Down
NIAG	NATO Industrial Advisory Group
NIR	Near Infra Red
RC	Remote Control
RF	Radio Frequency
RF	Reference Frame
RoE	Rules of Engagement
RSM	Research Specialists' Meeting
RTG	Research Task Group
S&T	Science and Technology
SAS	Systems Analysis and Studies (STO Panel)
SCI	Systems Concepts and Integration (STO Panel)

SET	Sensors and Electronics Technology (STO Panel)
STO	NATO Science & Technology Organization
SWIR	Short Wave Infra Red
sUAS	Small Unmanned Aerial Systems
TER	Technical Evaluation Report
TiAl	Titanium aluminide
UAS	Unmanned Aerial Systems
UAV	Unmanned Air Vehicle
UCAV	Unmanned Combat Aerial Vehicle
UV	Ultra Violet
VSTOL	Vertical Short Take Off and Landing
VTOL	Vertical Take Off and Landing

Revision History

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2.0	Jul 2021	Paolo Proietti	Final Issue

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Low, Slow, Small Threats Modelling and Simulation

(STO-TR-MSG-154)

Executive Summary

Modelling and Simulation encounters some unique challenges and opportunities from the physical and dynamic points of view, when it comes to considering small Unmanned Aerial Systems (sUAS), commonly known as drones, within the context of threat vectors.

The parametric definition of a drone comprises the following categories:

- Typology, referred to the mode that the drone can fly;
- Material used to manufacture the drone;
- Flying performance;
- Kind of propeller;
- Reference to NATO Classification;
- Navigation system;
- Remote controller characteristics (if any);
- Payload, considering both own sensors and possible hazards; and
- Communication Systems.

An analytical model describing the flight dynamics of a drone should be mathematically sound, since mission capabilities strongly depend on vehicle configuration and behaviour.

Considering that the motion dynamics of a rigid body in space requires a reference frame fixed to the body itself for a suitable a mechanical description, and making some assumptions (e.g., rigid body model, stationary atmosphere and no perturbations, symmetrical airframe, and forces acting in the centre of gravity), the Newton-Euler equations can be developed for flight dynamics of an sUAV.

When it comes to detecting sUAS, several phenomena have to be considered, such as reflectance on and outside the visible wave range, radio frequency, acoustics, and the related technologies, such as passive and active imaging and detection.

Since it has been asserted that multiple sensors are required to have the capability, and the probability of detecting sUAS, it is necessary to consider the identified parameters in order to model the signature against different type of detectors. In addition, the dependence of multiple sensors would also require advancements in information fusion and ensemble learning to ensure that actionable intelligence will be derived from complete situational awareness.

The Specialists' Meeting on Drone Detectability has stated the possibility of modelling radar signatures, as well as the acoustic signature for different drones, radars, and scenarios to complement experimental data and to help development of tracking, classification, and situational awareness algorithms. Furthermore, the suitability for radar scenarios simulation and their potential use for targets' modelling and feature extraction has been confirmed.

Nevertheless, a clear modelling of the drone signature with respect to its characteristics, both physical and dynamic, seems not easily feasible due to the complexity and variability of the drones on the market and their continuous enhancements.

The complexity and variability of the characteristics of sUAS makes it very difficult to accomplish the task of defining a model suitable to be used in a simulation system. This is due both to the several parameters that characterise the drone itself, and the complexity of the flight dynamics equations required to take into consideration all the drone's manoeuvrability capabilities and features. Furthermore, the complexity and variability of the characteristics of sUAS do not allow the definition of a parametric model for assessing the relevant signatures.

This means that, unfortunately, the objectives of the MSG-154 Study cannot be successfully achieved.

Modélisation et simulation des menaces faibles, lentes et légères
(STO-TR-MSG-154)

Synthèse

La modélisation et la simulation présentent des défis et des opportunités uniques en leur genre pour contrer les petits UAS, couramment baptisés « drones » dans le contexte des vecteurs de menaces considérés du point de vue tant physique que dynamique.

La définition paramétrique d'un drone comprend les caractéristiques suivantes :

- Typologie, désignée par le mode dans lequel vole le drone ;
- Matériau servant à fabriquer le drone ;
- Performances de vol ;
- Type d'hélice ;
- Référence à la classification OTAN ;
- Système de navigation ;
- Caractéristiques de la télécommande (le cas échéant) ;
- Charge utile, prenant en compte à la fois les capteurs propres et les dangers éventuels ; et
- Systèmes de communication.

Tout modèle analytique décrivant la dynamique de vol d'un drone doit être mathématiquement rigoureux, dans la mesure où les capacités de la mission dépendent largement de la configuration et du comportement en vol.

Étant donné que la dynamique de mouvement d'un corps rigide dans l'espace nécessite un cadre de référence fixé au corps lui-même pour obtenir une description mécanique convenable, et sous réserve de certaines hypothèses (par exemple, modèle de corps rigide, atmosphère stationnaire et absence de perturbations, cellule symétrique, et forces agissant au niveau du centre de gravité), les équations de Newton-Euler peuvent être écrites pour la dynamique de vol d'un sUAV.

Au plan de la détectabilité d'un sUAS, plusieurs phénomènes doivent être considérées, comme la réflectance dans et en dehors du spectre de longueurs d'ondes visibles, la fréquence radio, l'acoustique, et les technologies correspondantes, telles que l'imagerie et la détection passives et actives.

Sachant qu'il a été affirmé la nécessité de disposer de plusieurs capteurs pour avoir la capacité, mais aussi la probabilité, de détecter des sUAS, il convient de prendre en considération les paramètres identifiés afin de modéliser la signature pour différents types de détecteurs. En outre, la dépendance de plusieurs capteurs nécessite l'amélioration de la fusion des informations et de l'apprentissage d'ensemble de sorte que des renseignements actionnables puissent être tirés de la connaissance complète d'une situation.

La Réunion des spécialistes sur la détectabilité des drones a conclu à la possibilité de modéliser aussi bien les signatures radar que les signatures acoustiques de différents drones et radars, ainsi qu'à celle de scénarios visant à compléter les données expérimentales et à concourir au développement d'algorithmes de traçage, de classification et de connaissance situationnelle. De même, l'adéquation à la simulation de scénarios radar et à leur usage éventuel dans la modélisation de cibles et l'extraction de leurs caractéristiques a été confirmée.

Pour autant, une modélisation précise de la signature d'un drone à partir de ses caractéristiques, physiques comme dynamiques, ne semble pas aisément réalisable, du fait non seulement de la complexité et de la variabilité des modèles existant sur le marché, mais aussi de leurs perfectionnements permanents.

La complexité et la variabilité des caractéristiques des sUAS font qu'il est très difficile d'accomplir la tâche consistant à définir un modèle utilisable dans un système de simulation. Cela s'explique à la fois par les différents paramètres caractérisant le drone lui-même, et par la complexité des équations de dynamique de vol prenant en considération l'intégralité des capacités et des caractéristiques de manœuvrabilité du drone. Qui plus est, la complexité et la variabilité des caractéristiques des sUAS ne permettent pas non plus la définition d'un modèle paramétrique ouvrant la voie à l'évaluation des signatures voulues.

Cela signifie malheureusement que les objectifs de l'Étude MSG-154 ne peuvent pas être atteints.

LOW, SLOW, SMALL THREATS MODELLING AND SIMULATION

1.0 MSG-154 STUDY

1.1 Introduction

Several sources and studies in the recent literature have tried to categorise the Low, Slow, and Small (LSS) aerial platforms [1], [2]. These categorisations are mostly related to classification based on UAS Classes, but there has been a clear lack of categorisation with respect to the physical characteristics and capabilities specific to each drone.

The goal of the MSG-154 study [3] is to define LSS models applicable to synthetic environments for the development and deployment of appropriate defensive measures to counter potential future LSS threats. Any country-unique requirements are identified along with a recommended disposition for accommodating the uniqueness.

1.2 Purpose

The aim of the study is to take into account the variety of commercially available LSS aerial platforms in order to define LSS models from different points of view, and to make such models available for analysis and design aspects that apply to Counter-LSS (C-LSS) systems, for both detection and neutralisation. A classification scheme is appropriate for friendly and hostile LSS so that the tactical use and deployment, and the countermeasures strategies can be explored across a broad range, before solutions based on a single platform are lined up. Care has to be taken to ensure that the categorisation system is consistent with current NATO efforts; it must also be hierarchical so that various types of scenarios and levels of fidelity in simulation models can be employed. For example, there is little information on the flying characteristics of UASs, including the LSS.

The LSS can be modelled with respect to:

- Behaviour during flight;
- Signature against different type of detectors;
- The threat itself;
- Defence tactics; and
- User interface (including ability to fly beyond line of sight).

Consequently, the MSG-154 Study is organised in the following work packages:

LSS categorisation, in order to summarise the variety of aerial systems available on the market with respect to different characteristics and parameters that build upon and expand existing classification systems.

LSS physical modelling, to model behaviour during flight, covering the related flight profile, including the available manoeuvres and the impact of meteorological conditions (wind, rain, etc.) on them. Because commercial drones are able to fly in open space without any constraints and their small size and the light weight make them easy to manoeuvre and greatly sensitive to the external environmental conditions, accurate modelling is required for:

- Flight Profile.
- Navigation and collision avoidance mechanisms/algorithms.

- Kinematics affected by wind and other meteorological effects.
- Payload.
- Flight duration.
- Physics of impact (for example heavier UAVs do more damage to less fortified objects).
- Conditional behaviour/algorithms to disruptions like GPS or RC jamming.
- Human interface.
- Pre-flight waypoints/navigation.
- View method (Beyond Line of Sight, FPV, Stereo, etc.).
- Controllers (separate altitude and yaw, throttle, altimeter, etc.).
- Controller to LSS max range.

LSS detectability modelling, to model the signature against different type of detectors, since it has been asserted that multiple sensors are required to have the capability, and probability, of detecting such small objects. Further to the previous task, environmental conditions (day, night, fog, rain, etc.) could change detection capability considerably:

- Signature (radar, acoustic, thermal, etc.).
- Visibility in different conditions (day, night, fog, etc.) and environment (open space, urban, etc.).

LSS intelligence modelling, to model the threat itself, in order to model suspicious behaviours that could help to identify a foe object:

- Suspicious manoeuvring.
- Hazardous payloads.
- Most probable behaviour in certain environments, conditions or scenarios such as:
  - Probability of UAV misuse by potential hostile nations/groups.
  - Most probable LSS avenues of approach.
  - Most probable way of LSS misuse/attack.
  - Most probable affected area when using certain type of UAV.
  - etc.

Tactics modelling, to model the defence tactics to be simulated for the proper neutralisation of threats:

- Rules Of Engagement.
- Modelling effective ways of passive defence like ballistic nets, masking, hostile operator finding, etc.
- Modelling effective ways of active defence like RC jamming, video signal jamming, take-over the control, DEW attack effectiveness, C-RAM attack effectiveness, anti-air-artillery effectiveness, missile attack effectiveness, etc.
- Reaction models like estimated time for reaction (when e.g., flying 60 km/h and detected 1 km far from the defended post, the reaction time is approximately 1 minute), etc.

To create a high fidelity LSS models would require a large amount of on field measurements which is out of the scope, and the time frame of the Study, so some generalisation will be made during the activity.

1.2.1 Study Objectives Update

During the Study it was recognised that the group did not have adequate knowledge and expertise to successfully accomplish all the Study objectives.

To mitigate this lack, external experts from academia were asked to provide support for LSS modelling during flight and to prepare the related report section.

With regard to LSS detectability modelling, it was decided to organise a dedicated Specialists' Meeting inviting subject matter experts. This Meeting was held in April 2021. The results are summarised in the related section of this report [4], [5], [6].

Furthermore, due to the delay caused both by the above-mentioned lack of expertise and the COVID-19 pandemic situation, the remaining tasks related to LSS Intelligence Modelling and Tactics Modelling have been deleted from the MSG-154 Programme of Work, in agreement with the NATO Modelling & Simulation Coordination Office and the MSG Group. Therefore, this report will no longer address such points.

1.3 Other NATO Studies Synergies and Complementarities

The MSG-154 Group derives its activity from dedicated NIAG Studies to Counter LSS [7], [8], [9], in which specific technologies for detection and neutralisation were identified. The MSG-154 activity also cross-relates to SCI-301 on "Defeat of Low Slow and Small (LSS) Air Threats" [10]. Members from both study groups have been involved in this study in order to maximise the synergies.

In particular, the SCI-301 Study will address the modelling and simulation of the other components of a Counter-LSS System.

Moreover, this study would be co-beneficial to other STO studies on the topic, such as:

- SET-180 on "Analysis and Recognition of Radar Signatures for Non-Cooperative Identification of UAVs" [11];
- SET-200 on "Electromagnetic Scattering Prediction of Small Complex Aerial Platforms for NCTI Purposes" [12]; and
- SET-260 on "EO/IR Detection and Tracking of Small UAVs in an Urban Environment" [13].

2.0 RATIONALE

2.1 Background

Recent events worldwide have highlighted the rapid proliferation of Low, Slow and Small (LSS) platforms commonly identified as "drones", which brings with it a new and rapidly increasing threat to national defence and security agencies.

In addition to the demonstrated military application of Unmanned Aerial Vehicle (UAV) platforms, the employment of small and possibly modified commercial off-the-shelf UAVs by non-state or terrorist organisations poses a real and significant threat to high profile domestic and international events.

Many of the reports of LSS incidents seem to indicate that there was no malicious intent behind such incidents [14], [15], [16]. Nevertheless, the rapid evolution and worldwide spread of that technology, coupled with the easy purchasing of off-the-shelf platforms, has made defence against the LSS threat a real concern for NATO. Such a threat may be exemplified by the use of these platforms is in the Mosul battle, where the Daesh used a variety of drones, improvised and modified, to spread fear as well as to cause the most possible damage [17].

Even the threat from mini-UAV has been well understood since early 2000s [18] and LSS aerial platforms are now recognised as posing significant threats to NATO member nations and also to deployed coalition Forces. The primary LSS threat comes from three classes of minor UAVs – Micro, Mini and Small – because these UAVs can reach very close proximity and can avoid being recognised early enough to trigger appropriate response.

To date, the emphasis has been on the use of the LSS class of UAVs in an ISR mode, but attack modes e.g., in the form of flying IEDs are more than likely and have been already tested. The rapid evolution and worldwide spread of technology, as well as the evolution of artificial intelligence algorithms that allow autonomous modes of operation coupled with the easy purchasing of the off-the-shelf platforms, has made the NATO defence against the LSS threat a real concern. The easiest way to test all potential scenarios in the safe environment is to use experimental frameworks [19], [20] and to follow existing standards and best practices already existing in the domains of modelling and simulation and of autonomous systems [21].

2.2 The Threats

In the future, defence planners should consider as feasible LSS attack missions and flight profiles that could be transferred from a national military to a terrorist organisation. This is particularly true for the LSS, as these can be operated by a small number of people and do not require any large support infrastructure. In fact, most of NATO Armed Forces are already testing fictive scenarios that inject UAV misuse incidents.

Many experts consider that the small and mini drones have the greatest potential to impact national security and privacy, because they can be easily acquired, transported at any time and everywhere and can fly almost undetectably due to their extremely low signature. Small and mini drones are already a military operational option, but micro-drones are increasingly being used thanks to their unique features: extraordinary manoeuvring capability, cruise speed, etc. As technology continues to advance, it will become easier and less expensive to build even smaller drones that are able to fly longer, carry heavier loads, withstand more Gs or proceed more sophisticated attack or evasive manoeuvres.

The variety in shapes, sizes and capabilities of unmanned vehicles/systems is due to the diversity of the missions they are designed to accomplish or are capable to perform. Their use was initially conceived for reconnaissance and surveillance operations, but their use is slowly fading towards operations that are more and more focussed on offensive and combat missions.

The flight characteristics of many of these mini and micro platforms pose some challenges to current ground-based systems and infrastructures. In order to develop and deploy appropriate defensive measures to counter future threats from LSS, NATO and Nations are launching a series of programmes to identify cost effective measures for detection, classification, tracking and neutralisation of any potential threats from LSS.

Recently, the technology of LSS has been proliferating and maturing in the civilian/commercial sector, which has led to wider commercial, and leisure-time use of LSS platforms. This evolution continues to demonstrate the very rapid rate of change with regards to the use of materials, energy-efficient propulsion, navigation, control and autopilots, data links and sensor and effector payloads.

LSS systems are becoming increasingly more capable and more readily available. Some types of LSSs are available for “off-the-shelf” procurement. Also, systems with limited technologies and capabilities, such as those employed by the hobbyist-driven markets for model aircraft, have long been widely available at a relatively low cost. Many of these commercial systems have Software Development Kits (SDKs) allowing their owners to programme behaviours that are suitable to harmful intents.

However, systems with larger payload capacities and improved capabilities are now becoming more readily available. Also, the business competition is dramatically downsizing prices. Thus, more and more individuals can afford to buy quite capable types of UAVs that may also be more dangerous if misused.

All these factors and the improving attributes of the commercial UAV platforms lead to an unprecedented need for effective sets of defensive measures. One of these measures is the ability to simulate LSS behaviour in an artificial environment and its models, and to study ways of understanding how to act efficiently against LSS.

To properly address issues surrounding LSS it is important to classify these vehicles and to get a shared definition of which features define a LSS. For example, it could seem logical to delineate fixed wing from rotary wing LSS, but other delineations would become then more difficult. For example, should tethered vehicles be included among LSS? Which specific feature qualifies a LSS as ‘low’ or ‘small’ or ‘slow’? Different member nations in NATO may have different qualities and definitions for each of these. Thus, it is necessary first to gather data about features, then to state classification categories.

3.0 STUDY OBJECTIVES

3.1 Objectives

According to the Final Report of the NIAG Study SG-200 [9], the complexity of countering the LSS threat necessitates more effective use of modelling and simulation tools to aid the user community. These simulation tools are needed to underpin the operational benefit analysis that is required to support acquisition programmes of C-LSS, to aid the operational staff while planning the deployment of C-LSS and to aid in the required operational training programmes [22] that pursue the following goals:

- Verification and Validation activities that represent a substantial part of the total investment in the product lifecycle.
- Verification and Validation Strategy to be defined as early as possible as:
  - To evaluate the impact/drive on design choices.
  - To evaluate all cost items for the System Business Case.
- Instructional design activities to arrive at an optimal suite of training strategies for operating and countering the use of LSS in various operational scenarios.

Figure 1 depicts the operational concept of the synthetic environment for a Counter-LSS System composed of:

- All the simulated components of the system (i.e., models of sensors, effector, and data processing);
- A simulated environment (e.g., weather conditions, etc.);
- An Air Defence simulator; and
- Input of the simulated threats.

This operational concept is needed in order to perform a real time simulation of the previous validated models that will enable evaluation of the performance and operational suitability of a given system and to measure it.

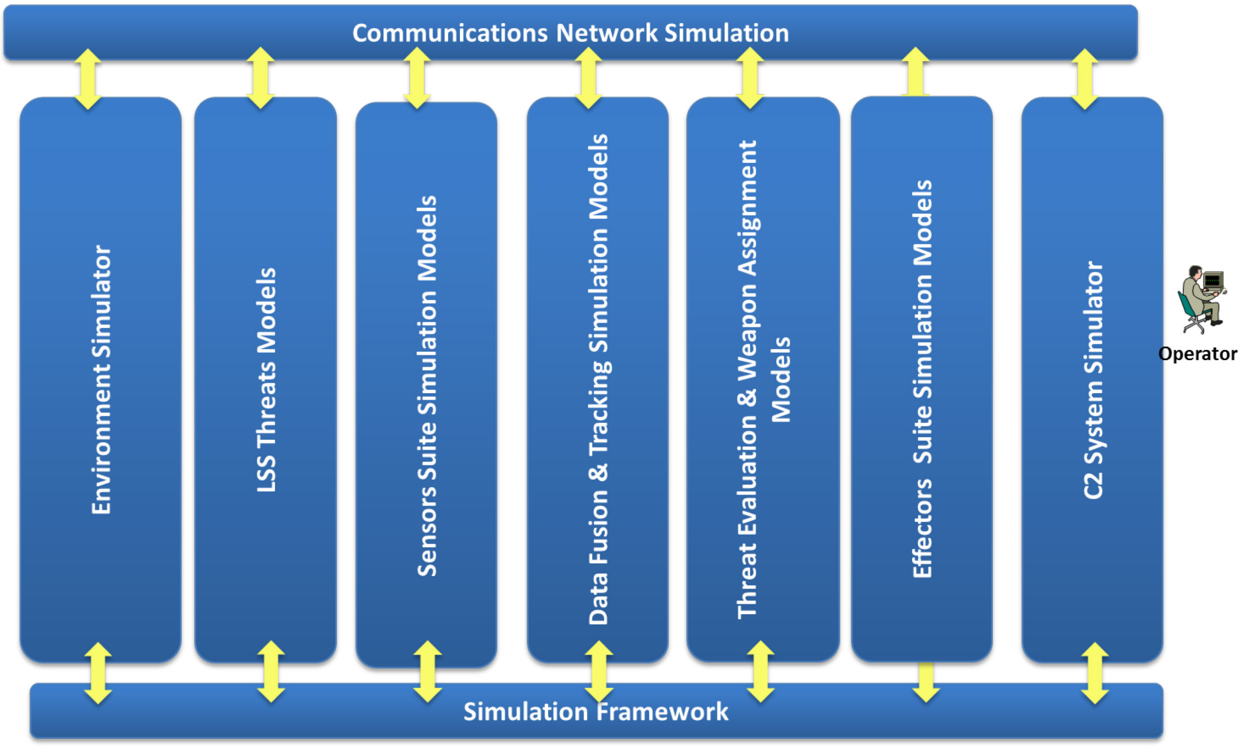

Figure 1: C-LSS Simulation Operational View.

3.2 Simulation Architecture

From a general point of view, a simulation environment is typically composed of:

- Simulation Framework, based on an exchange protocol (e.g., DIS/HLA);
- Own platform(s) modelling, meaning mathematical and logical modelling of the entities of interest. In this case one or more LSS and opposing entities.
- Modelling Tools, meaning the services to describe the actors (e.g., sensors and effectors) for implementation at different levels;
- Environment Representation, including terrain, weather, 3D model of an urban environment (e.g., big cities, critical infrastructures, …); and
- Training Audience, including resources to support visualisation, simulation control, analysis tools for the users. This also includes scenario generation, exercise control, and after-action review.

In this context, the typical Simulation Architecture, where all the system components are simulated, is outlined in Figure 2.

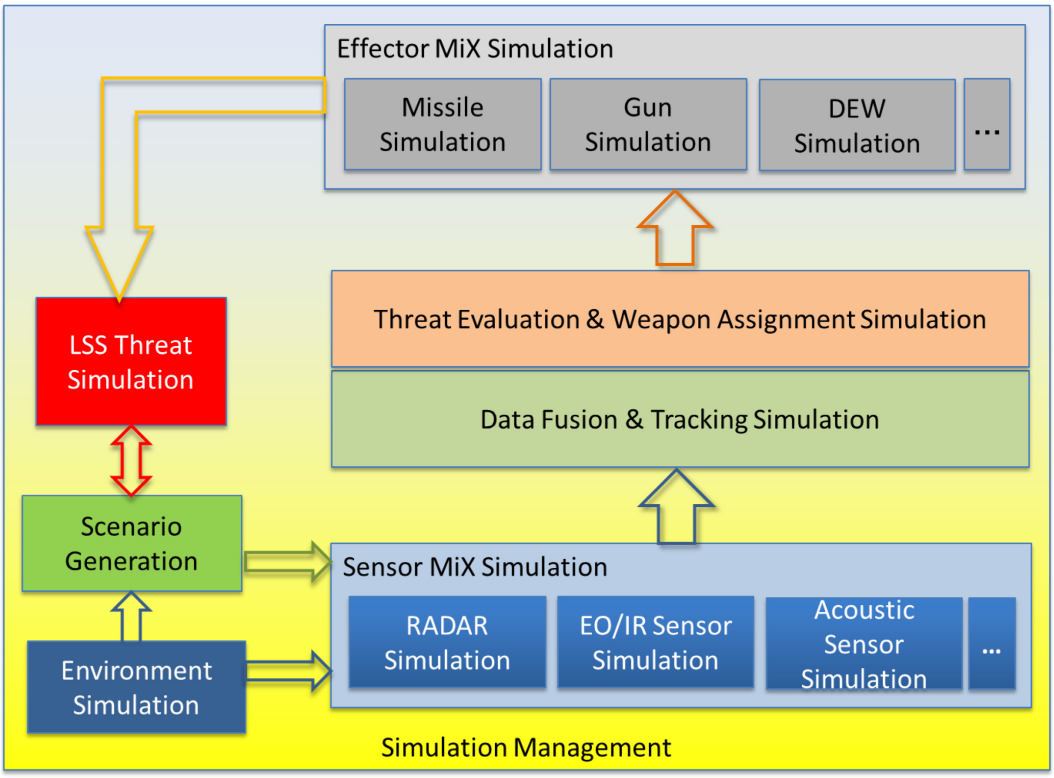

Figure 2: C-LSS Simulation Architecture.

4.0 LSS CATEGORISATION

4.1 Introduction

The first task accomplished by the Study Group is related to LSS Categorisation, which defines a set of parameters to be used in model definition. Of course, such a set is not exhaustive, and it could be improved as necessary.

The main identified categories are:

- Typology, referred to the mode that the drone can fly;
- Material used to manufacture the drone;
- Flying performance;
- Kind of propeller used;
- Reference to NATO Classification;
- Navigation system used;
- Remote controller characteristics (if any); and
- Payload, considering both own sensors and possible hazards.

For each of the above-mentioned categories a number of parameters have been identified, as depicted in the following sections.

Once all the parameters are identified they will be used for model definition and, if necessary, further expanded. Parameters will be cross checked against any national restrictions and annotated accordingly.

4.2 Typology

This category sorts commercial UAVs according to their type/shape (Table 1), which also influences other UAV capabilities such as maximum speed, rate of turn, etc. (for inter-category causality, see Figure 3 and Figure 4 in Section 4.12). Today, commercial UAVs are mostly based on fixed or rotary wing bases, but their technological evolution brings some new types of UAVs like the VTOL (combined rotary/fixed wing). To describe today's types and anticipate the types of UAVs of the near future could help the modelling and simulation process to be prepared for unusual combinations of UAVs construction. Some parameters mentioned in the Typology category are still used mostly in military domain (like flapping wing UAVs) however, the commercial sector shows flexibility in making new types of UAVs available on the market very quickly.

Table 1: Typology Category.

Typology
Fixed Wing
Rotary Wing
Combined Rotary/Fi Wing (VSTOL)
Flapping Wing
Airship/Balloon (aka lighter than air)

4.3 Dimension

This category is probably one of the most important categories (together with the Performances category) for modelling and simulation purposes (Table 2). The smaller the UAV, the harder its detection and visibility. Vice versa, the bigger the UAV, the more payload or fuel it could bring, etc. The dimension factor is also very hard to simulate, to avoid providing the user with a false perspective of the scene. To make realistic models, we need to well simulate not only proper dimensions but also proper visibility at given distances (that might be influenced for example by simulated atmosphere permeability, UAV colour visibility, UAV material refraction, etc.). Generally speaking, of course the bigger the UAV, the better its visibility.

Table 2: Dimension Category.

Dimension
Total Length
Total Height
Total Depth
Wingspan (fixed wing)
Rotor Diameter (rotor wing)
Rotor/engine distance
Body Diameter (airship/balloon)
Weight

4.4 Material

Today commercial UAVs are usually plastic-made to be not too expensive. Other materials are the domain of professional UAV users like entertainment companies, professional photographers, survey companies, etc. However, in the near future we can expect a slowly progressing proliferation of better quality materials for cheaper commercial UAVs (completion, higher UAV performance). Better materials (HiTech, metal, etc.) provide a UAV with better capabilities for reaching its limits in speed, ceiling, rate of turn, etc. There is also another factor – spectral visibility – that is stressed in modelling and simulation. Each material has different spectral visibility in certain environment conditions and when observed by different sensors. For example, the chassis of plastic-made UAVs has almost zero radar-cross section, but it is permeable to heat and electromagnetic energy; thus, the UAV engines radiate more energy outside the drone. That is why we need to cover future models by simulating the materials they are made of, too (Table 3).

Table 3: Material Category.

Material
Metals
Aluminium
Steel
Composites
Graphite
Carbon
Glass
Resins
Thermoset Resins
Thermoplastic Resins
Polymers
Plastic
Other Materials
Wood/paper
Inter-metallics
Hi Tec material

Aluminium is extensively used in aerostructures including drones; it has several advantages including moderately low cost; ease of fabrication which allows it to be shaped and machined into structural components.

Steel is the most commonly used metal in structural engineering even though it has a high density. Steel is still an option for aerostructures from small sizes to bigger ones.

Although **graphite** is a material extensively used for aerospace industry, it is not the only alternative material for composite structures. **Carbon** and **glass** (generally in form of fibre) are main reinforcement materials. (Fibre/Particulate form)

Polymers are the most widely used materials for composites as matrix material. Commercial and high-performance aerospace applications of these composite materials are comprised of **thermoset resins**; the other most commonly used matrix type is thermoplastic resin. Resins have a critical role for mechanical properties of materials, moreover resins are key components for Radar Absorbing Materials.

Nylon 6.6, Acrylonitrile Butadiene Styrene (ABS), polycarbonates are some of examples of **plastics**. In recent years, 3D printing has been a very popular production method for industry, which has brought ABS to the forefront. ABS plastic is a common thermoplastic polymer used for 3D printing prototype development and injection moulded part manufacturing.

Inter-metallics are generally used for high temperature applications. The most popular one is TiAl. GEnx[1] and LEAP engines are some examples of these materials' applications. Intermetallic seems not to be a possible option for LSS platforms.

4.4.1 Material Properties

Table 4: Material Properties Category.

Property
Temperature
Thermal Emissivity
Electromagnetic Absorbance
Radiance
Light Absorbance
Colour
Luminosity
Reflectivity
Scattering
Transmittance
Acoustical Absorption
Sound Reflection
Surface Roughness

4.5 Performances

This category is probably the most important in the list. The performances of a UAV shape the set of capabilities that are crucial for the way that UAV is not just used, but also misused. Each parameter is important because it may limit or enable UAV use under certain conditions and for operations of a specific type/mode (Table 5).

[1] GenX is a chemical process that uses 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoic acid (FRD-903) and produces FRD-902 and E1. The process is proposed as a replacement for the use of toxic and carcinogenic PFOA (C8) for manufacturing fluoropolymers like teflon

Table 5: Performances Category.

Performances
Ceiling
Max Cruising Speed
Empty
Max Loaded
Normal Mission Radius
Endurance
Empty
Max Loaded
Rate of Climb
Rate of Descent
Rate of Turn (manoeuvre)
Rate of pitch
Rate of roll
Rate of yaw
Rate of Turn (wrt own axis)
Rate of pitch
Rate of roll
Rate of yaw
Maximum Weight at Take-Off (MWTO)
Day and/or night operations
Ability to operate in inclement conditions (rain, fog, etc.)
Performance limitations in wind
Manoeuvrability Volume (x,y,z)

- **Ceiling** [m] – this parameter is related to the ability of a UAV to fly higher, so that its visibility from the surface decreases. The maximum ceiling also allows the UAV to operate more silently or to cover larger area through its sensors. In the case of commercial UAVs, ceiling is limited by international laws (ICAO rules) to 300 meters Above the Ground Level (AGL) for leisure/hobby purposes, but some states are even more restrictive. For modelling and simulation purposes, we need to know the approximate maximum altitude of a UAV; if a given specific model has the hardware/software maximum ceiling limiter; and if it is possible to easily turn off this limiter (not by possessing extra electro-technical education) – in other words, if we can expect the UAV to be operated at higher altitude.

- **(Maximum) cruising speed** [m.s-1] – this crucial parameter does not just provide information about the maximum UAV speed, but it also limits possible defensive counteractions against it. If the UAV is small enough to be visible/detectable only from a short distance and it also flies very fast (today some micro UAVs can reach 100 km/h speed), then counteractions must be performed within the horizon of a few seconds not tens of seconds or minutes. This parameter has two sub parameters that limit the usage of a UAV: maximum cruising speed when it flies loaded; maximum cruising speed without any load (it means with only on-board sensors and systems).

- **Normal mission radius** [km] – it is very hard to determine this parameter, because it is usually connected with the goal of the mission and with the mission tactics. For example, if a UAV is to attack some asset and the mission is planned with deception manoeuvres, that UAV will not fly directly but will change its route. The maximum radius will also be different if the mission is simply a reconnaissance mission (with on-board sensors only) or if it is offensive (with weapons or explosive on board). Further research should solve the need of sub parameters, here.

- **Endurance** [min] – this parameter is usually defined as the ability to withstand some conditions without any harm or interruption. Here, the UAV can fly when operated normally (without any extreme manoeuvres or limits pushing) during a period. There are two sub parameters: endurance if operated unloaded or with maximum load. Today commercial UAVs can be operated approximately for 20 – 40 minutes (with original battery pack and when unloaded), e.g., DJI Phantom II Vision or DJI Mavic Pro.

- **Rate of climb, rate of descent** [m.s-1] – these two parameters are similar, however usually they do note feature the same value. Especially today, rotary wing x-copters are designed to climb faster than to descend, because ordinary users do not usually have proper training to land the UAV safely (e.g., the DJI Mavic drone has an ascent speed of 5 m.s-1, while descent speed is 3 m.s-1). This can shape the model behaviour.

- **Rate of turn** [deg.s-1] – this parameter is important when simulating the UAV flight path. Fixed wing UAVs usually need more time than rotary wing UAVs to perform a 180° (or 360°) turn. Some x-copters, especially mini and micro ones, can change direction almost instantly, so they are able to do 180° turn in less than a second. Further research should clarify whether the MSG-154 will categorise this parameter as the “standard rate of turn” that is also used in aviation, or other types of this parameter to better fit the x-copter’s capabilities.

- **Maximum weight at take-Off** (MWTO) [kg] – this parameter clarifies whether a UAV is able to fly with a payload that is not part of its original on-board equipment. Every commercial UAV is able to carry at least several grams in the form of external cameras or other sensors. Today, micro UAVs can carry a few grams or tens grams of payload, while mini UAVs can carry hundreds of grams or kilograms. This capability is very important if simulating the threat in the form of a load of hazardous substances.

- **Day and/or night operations** including any limitations in performance parameters – rather than a parameter (with defined SI unit), this performance category represents the ability or limitation of the above stated parameters when the UAV is operated in different day/night conditions.

- **Ability to operate in inclement conditions** (rain, fog, etc.) – this performance category could be defined as a matrix with yes/no statements or as a table with specifically described limitations in certain weather conditions. The form of this parameter will be the matter of further research, for now.

- **Performance limitations in wind** – this parameter could be taken as a subcategory of the “Ability to operate in inclement conditions”, but wind influence is an almost constant limitation factor for UAV flight, so here it has the separate parameter slot. The faster the wind, the more negative influence it has on smaller UAV types. Although there are sets of autopilot balance correction measures applied during UAV flight, there do exist limits to a UAV's ability to withstand the wind. UAV modelling and simulation should implement this factor.

4.6 Propulsion

This category influences several other parameters like maximum speed, rate of turn, etc. (Table 6).

Table 6: Propulsion Category.

Propulsion
nr of engines
Battery
Solar
Propeller(s) (e.g., gasoline)

4.7 Class (NATO)

This performance category serves more for categorisation than modelling and simulation however, it has its place in connecting current NATO classifications with MSG-154 research (Table 7).

Table 7: NATO Classification Category.

Class (NATO)
Micro
Mini
Small
Tactical
MALE
HALE
UCAV

4.8 Navigation System

Navigation System is a key category when describing UAV capability and survivability (Table 8). The more redundant navigation systems a UAV has, the better it is prepared for unexpected (or expected) circumstances. For example, GPS navigation is one of the most accurate types of navigation, on the other hand, the GPS signal can be very easily jammed because the signal power is very low on the Earth's surface. Another parameter of this category is visual navigation by on-board camera, transmitting the video to the operator. This would help the navigation to a certain point, but the range of such navigation is limited to signal power and even using the signal extender, the maximum range of such navigation (of commercial UAVs, not military using satellite communication) is very small.

Table 8: Navigation System Category.

Navigation System
Remotely piloted
RF
Tethered
GPS
INS
Visual
GSM
"Follow Me"
Artificial Intelligence
Video signal analyses and recognition
Navigation support system
None
Collision avoidance
Terrain following
Return to Home

4.9 Remote Control

Remote Control limits the maximum range of operator-controlled flight (Table 9). When modelling the UAV entity, this category and its parameters can significantly shape the final UAV model performance and capability. The model itself should probably contain not just the UAV itself but also the operator entity. Such bi-model could help to cope with the terrorist UAV misuse, because the defender should not focus just to enemy UAV elimination but also to enemy operator finding (small UAVs expect the operator in radius of hundred meters, maximum one or several kilometres).

Table 9: Remote Control Category.

Remote Control
Max distance
Method (RF, tethered)
Frequency
Max Transmitter power
Extenders for control signal
Extenders for video signal
Beyond visual line of sight capability
User display (e.g., FPV, stereo, etc.)
Delay between input and LSS response (min, max)
Route Planning

4.10 Payload (Sensors)

Every commercial UAV has its own on-board equipment, consisting of navigation, remote control and usually camera (Table 10). More expensive commercial UAVs have telemetry transmitting the flight data to ground station/operator. When modelling the possible misuse, other sensor types or ways of jamming should also be taken into account.

Table 10: Own Sensor Payload Category.

Payload (Sensors)
Camera
Spectral range (visual, IR, etc.)
Telemetry
Countermeasures
Reconnaissance tool

4.11 Payloads (Hazards)

This category is important from the perspective of misuse. Each model (if there is non-zero MWTO) can be “armed” with some type of hazardous load to simulate the offensive action against friendly assets/forces (Table 11).

Table 11: Hazardous Payload Category.

Payload (Hazards)
Chemical
Biological
Radiological
Nuclear
Explosive
Panic
Jammer
Payload container/grabber
Weapon delivery type
Deployment method (none, remote, other)

4.12 Parameters Interactions

Most of the parameters identified above are strictly related each other in terms of reciprocal influences.

For example, the way the drone can fly could take into account the audio frequency generated by the rotors, or the material used to construct a drone could be further considered with its characteristics related to physical units used in detection (e.g., reflectivity, EM absorption, etc.), or the temperature of the exhaust related to the propeller. Figure 3 and Figure 4 depict some of these relations.

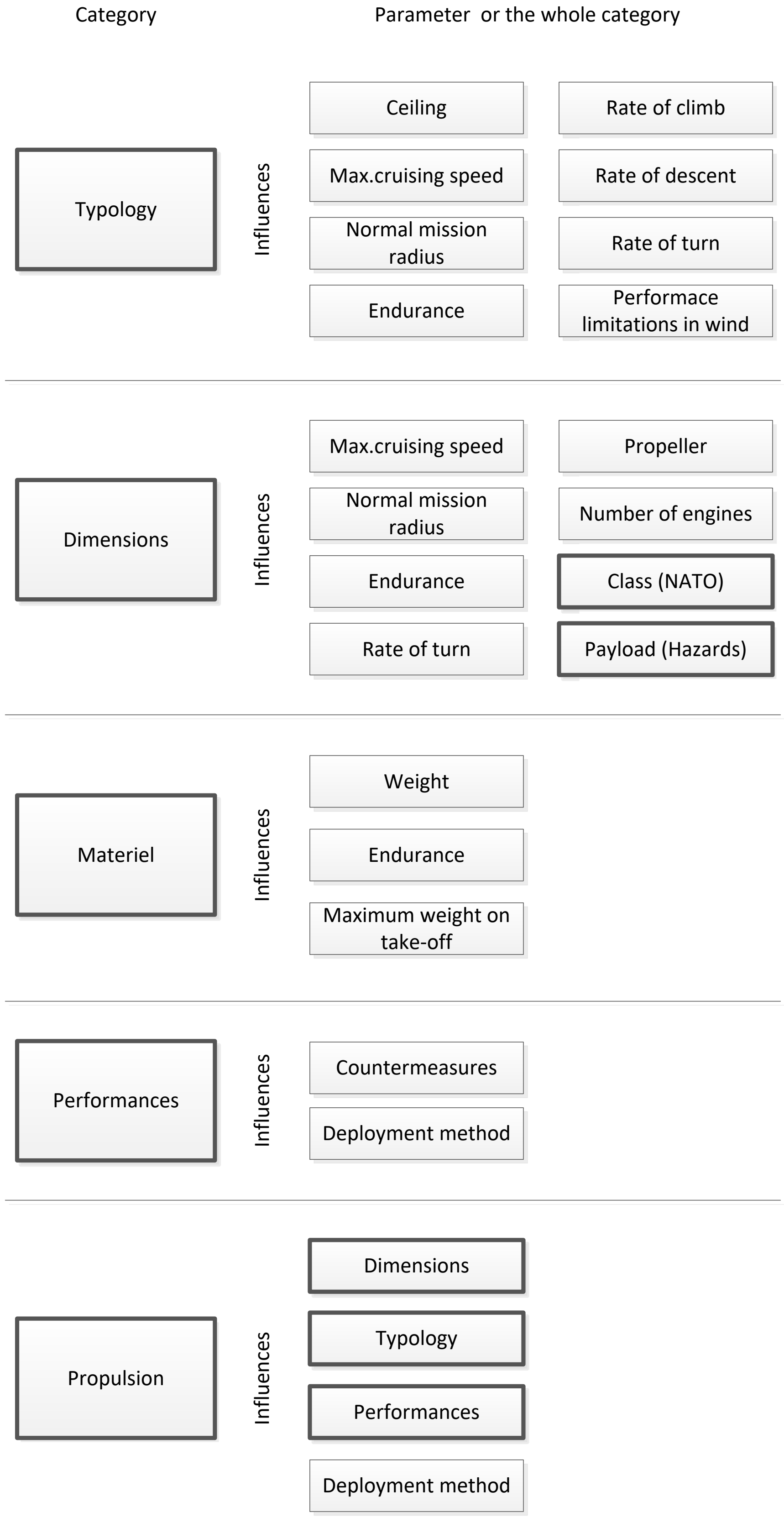

Figure 3: Relation Between UAV Categories and Other Categories/Parameters (Part 1).

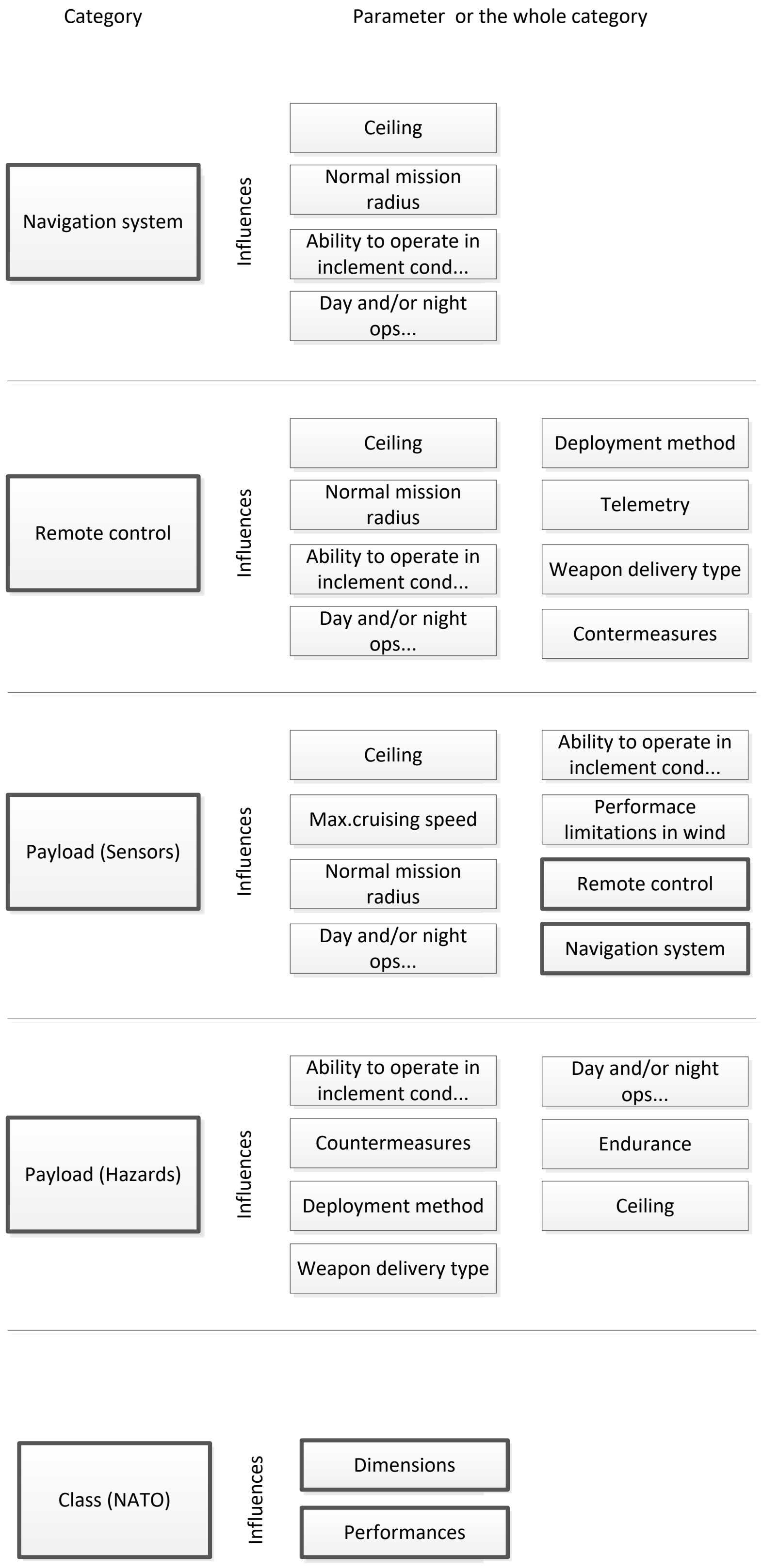

Figure 4: Relation Between UAV Categories and Other Categories/Parameters (Part 2).

5.0 LSS FLIGHT DYNAMICS MODELLING

Nomenclature **[23]**

(x^i,y^i,z^i)	Inertial frame axes
(x^v,y^v,z^v)	Vehicle frame axes
(x^b,y^b,z^b)	Body frame axes
Φ,θ,Ψ	Attitude angles, rad
α	Angle of attack.
β	Side slip angle.
χ	Course angle
χ_c	Crab angle
γ	Inertial-referenced flight path angle
u, v, w	Inertial velocity components of the airframe projected onto x*b*-axis
V_a	Airspeed vector
V_g	Ground speed vector
V_w	Wind speed vector
C_L	Aerodynamic lift coefficient
C_D	Aerodynamic drag coefficient.
C_{m*}	Aerodynamic pitching moment coefficient
C_{p*}	Aerodynamic moment coefficient along the *xb*-axis
C_{q*}	Aerodynamic moment coefficient along the *yb*-axis.
C_{prop}	Aerodynamic coefficient for the propeller.
C_{q*}	Aerodynamic moment coefficient along the *zb*-axis
C_{X*}	Aerodynamic force coefficient along *xb*
C_{Y*}	Aerodynamic force coefficient along *yb*
C_{Z*}	Aerodynamic force coefficient along *zb*.
δ_a	Aileron deflection
δ_e	Elevator deflection
δ_r	Rudder deflection
δ_t	Throttle deflection
f_D	Force due to aerodynamic drag
f_L	Force due to aerodynamic lift
m_b	External moment applied to the airframe
l, m, and n	Components of *m*b in mb
g	Gravitational acceleration (9.81 m/s^2)
Γ_*	Products of the inertia matrix
h	Altitude
ρ	Density of air
J	Inertia matrix
J_x, J_y, J_z, and J_{xz}	Elements of the inertia matrix
k_{motor}	Constant that specifies the efficiency of the motor
S_{prop}	Area of the propeller

5.1 Generalities

For any flying vehicle, including Unmanned Aerial Vehicles (UAV), mission capabilities strongly depend on vehicle configuration: the mathematical model that describes the flight dynamics of such vehicle should be very detailed [24], [25].

An airplane generally possesses 6 Degrees-of-Freedom (DoF) motion, with non-linear behaviour. The flight of an airplane can be modelled by non-linear coupled differential equations, taking into account the forces and moments acting on it. It is desirable that the mathematical model of an airplane (or UAV) be the simplest possible, yet precise and descriptive of the reality [25].

Similarly, the dynamics of a conventional multi-rotor configuration are relatively simple: the vehicle is controlled by changing the rate of rotation of the propellers. Most of the time, an even number of rotors is used. The most common configuration, named quad-rotor or quadcopter, features two pairs of rotors mounted at the ends of a simple cross-shaped structure, or at the corners of a square frame. Two rotors rotate in the clockwise direction and two rotate counter-clockwise, such that at hover each rotor produces a thrust equivalent to one fourth of vehicle weight, with zero pitch and roll moments and perfectly balanced rotor aerodynamic yawing torques (Figure 5) [24].

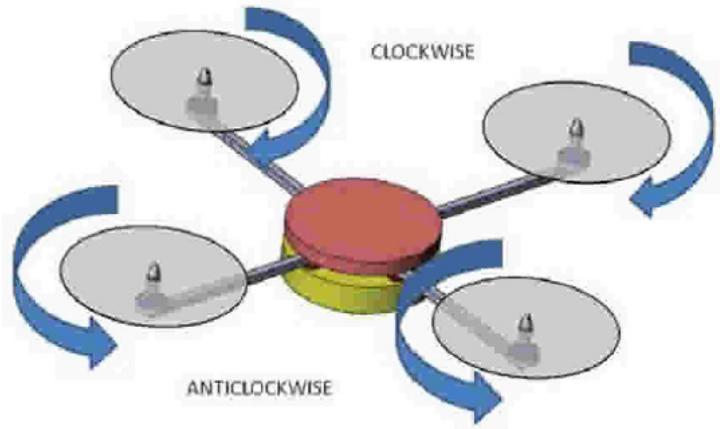

Figure 5: Direction of Rotation of the 4 Rotors.

To obtain the vehicle model, the following steps can be followed [25]:

- Define a set of reference systems;
- Describe the translational (sum of forces) and rotational (sum of moments) motions using Newton's Second Law;
- Make considerations in order to simplify the equations of motion, decoupling the longitudinal and lateral-directional dynamics;
- Chose the state variables;
- Apply frame rotations in order to obtain the flight dynamics equations in the desired frame of reference;
- Linearize the model around an equilibrium point (choosing a specific speed and altitude);
- Obtain the stability and control derivatives using specific software, CFD simulations, Wind-Tunnel test, virtual flight tests, or real flight tests;
- Calculate the aerodynamic forces using the stability and control derivatives.

5.2 Reference Axis Systems

To study the motion dynamics of a rigid body in space requires a mechanical description in a reference frame fixed to the body itself. Also it is useful to know the position and orientation of the body with respect to the Earth's surface [23], [24].

Three Reference Frames (RFs) are defined as follows (Figure 6) [23], [25]:

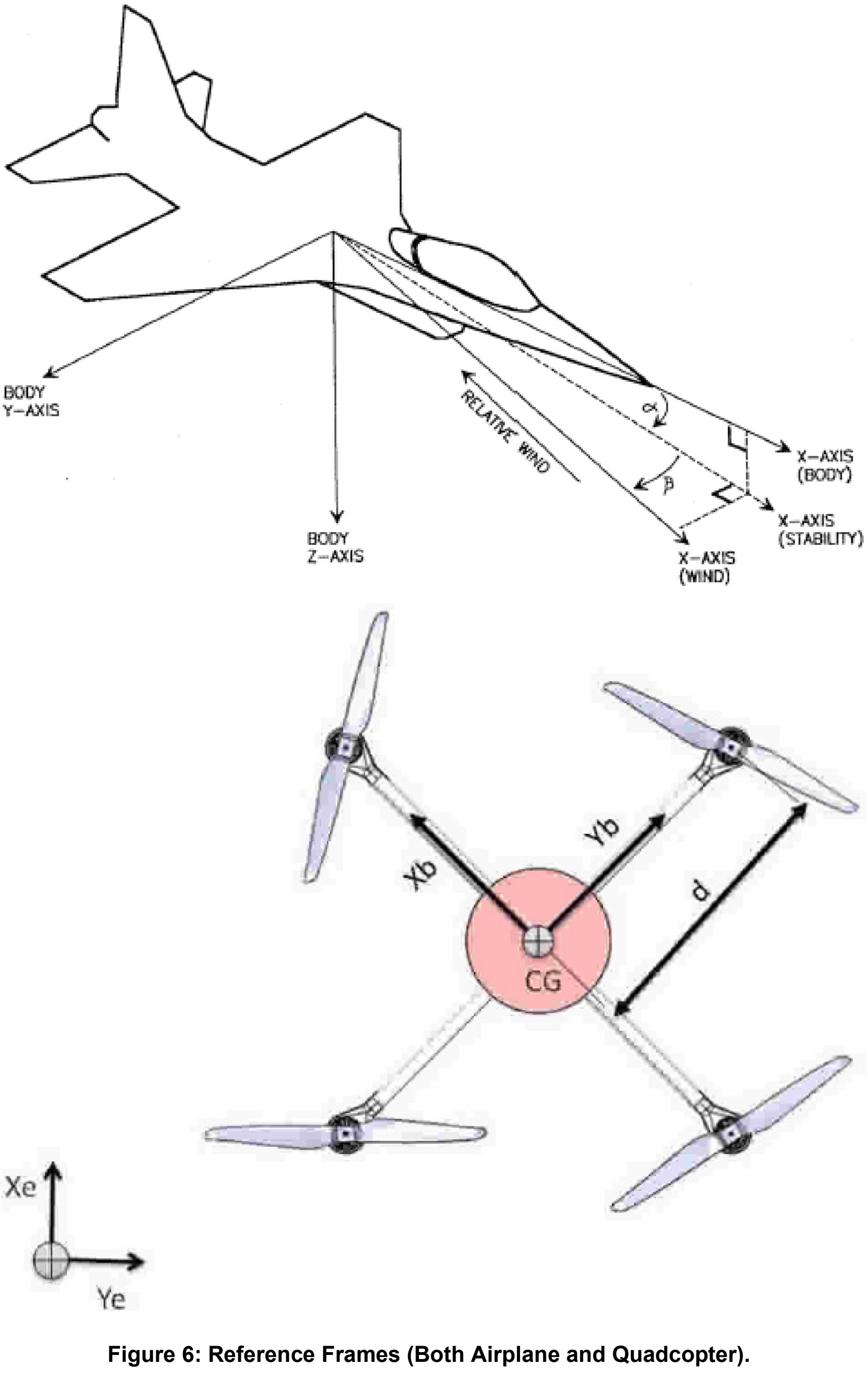

Figure 6: Reference Frames (Both Airplane and Quadcopter).

a) Body Axes – RF with 3 orthogonal axes, fixed on the aircraft CG. By convention, starting at the airplane CG, the X-axis is pointing to airplane's nose, Y-axis pointing to airplane's right wing, and Z-axis pointing to airplane's bottom;

b) Stability Axes – This RF is also known as North-East-Down (NED) frame. It has 3 orthogonal axes located at the airplane CG, with the X-axis pointing North, Y-axis pointing East, and Z-axis pointing down (to the Earth's centre);

c) Wind Axes – RF with 3 orthogonal axes, fixed on the aircraft CG. These axes always follow the relative wind direction, with respect to the airplane. The X-axis points in the reverse direction of the relative wind. The Z-axis is perpendicular with the relative wind and it points down. The Y-axis completes the system.

Therefore, an inertial referential frame is fixed in the ground:

d) Ground Axes System – RF with 3 orthogonal axes, fixed on the ground. The X and Y axes are parallel to the Earth's horizon (Flat Earth Model). It uses the NED convention.

One reference is the Earth's axis fixed frame chosen as inertial system: the first and the second axes of this frame are oriented to the North and to the East with the origin placed on the Earth's surface. The second reference frame is the Body axis reference frame whose origin is placed in the Centre of Gravity (CG) of the quad-rotor (Figure 6) [24].

5.3 Equations of Motion

The shape of the airfoil determines its aerodynamic properties, and some of its geometrical parameters. Some of aerodynamic parameters are shown in Figure 7 [23].

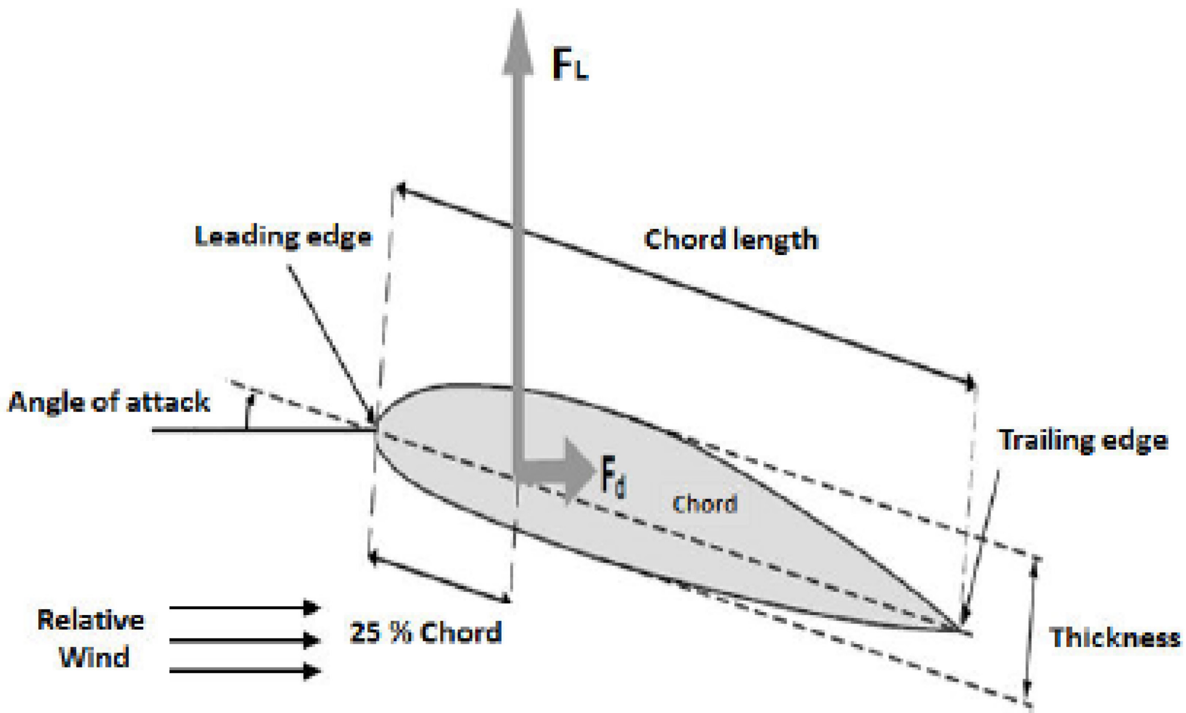

Figure 7: Section of Airfoil and the Applied Lift and Drag Forces.

The dynamics of the UAV are decomposed into longitudinal and lateral dynamics; each of these has some aerodynamic non-dimensional coefficients that affect the stability of the aircraft. These coefficients are parameters in the aerodynamic forces and moments equations and are influenced by the airfoil design [23].

- Longitudinal Aerodynamic Coefficients. The longitudinal motion acts in the *xb-zb* plane which is called the pitch plane and is affected by the lift force, drag force, and pitch moment.
- Lateral Aerodynamic Coefficients. The lateral motion which is responsible of the yaw and roll motions. It is affected by the side force, yaw moment, and roll moment.

The following are a summary of modelling equations used for the kinematics and dynamics of a UAV.

The basic assumptions are as follows [23], [24], [25], [26]:

- The UAV is in cruise flight phase;
- The atmosphere is stationary. The atmospheric properties only depend on altitude (i.e., they are independent of temperature variations and wind);
- The Earth's surface is considered flat (Flat Earth Model), with no acceleration, no rotation, no translation, and with constant gravity intensity and direction (perpendicular to the Earth's surface);
- The UAV body is considered rigid (rigid-body model) and with constant mass (mass is not a time function);
- The perturbations around the equilibrium point are small (small pitch angles around trim point);
- The elevator deflection does not change forces, only the pitch moment;
- All aerodynamic forces (Lift, Drag, Thrust) act in the UAV Centre of Gravity (CG);
- The UAV presents airframe symmetry in the x and z planes.

The following are the Newton-Euler equations developed for the flight dynamics of an UAV [26].

$$\begin{pmatrix} \dot{p}_n \\ \dot{p}_e \\ \dot{h} \end{pmatrix} = \begin{pmatrix} A & B & C \\ D & E & F \\ G & H & I \end{pmatrix} \begin{pmatrix} \mu \\ \nu \\ w \end{pmatrix}$$

where,

$$A = c\theta c\psi \qquad F = c\phi s\theta c\psi - s\phi s\psi$$

$$B = s\phi s\theta c\psi - c\phi s\psi \qquad G = s\theta$$

$$C = c\phi s\theta c\psi + s\phi s\psi \qquad H = -s\phi c\theta$$

$$D = c\theta c\psi \qquad I = -c\phi c\theta$$

$$E = s\phi s\theta c\psi + c\phi s\psi$$

$$\begin{pmatrix} \dot{\mu} \\ \dot{v} \\ \dot{w} \end{pmatrix} = \begin{pmatrix} rv - qw \\ pw - ru \\ qu - pv \end{pmatrix} + \begin{pmatrix} -mg\ s\theta \\ mg\ c\theta\ s\phi \\ mg\ c\theta\ c\phi \end{pmatrix} + \frac{1}{m}\begin{pmatrix} 0 \\ 0 \\ -F \end{pmatrix}$$

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & s\phi t\theta & s\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi \sec\theta & c\phi \sec\theta \end{pmatrix}\begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \frac{J_y - J_z}{J_x} qr \\ \frac{J_z - J_x}{J_y} pr \\ \frac{J_x - J_y}{J_z} pq \end{pmatrix} + \begin{pmatrix} \frac{1}{J_x}\tau_\phi \\ \frac{1}{J_y}\tau_\theta \\ \frac{1}{J_z}\tau_\psi \end{pmatrix}$$

where, $\boldsymbol{c\theta}$, $\boldsymbol{s\theta}$ and $\boldsymbol{t\theta}$ represent notation for cos θ, sin θ and tan θ. $\boldsymbol{pn}$ and $\boldsymbol{pe}$ are inertial North and inertial East position of the UAV. The altitude of the UAV also known as the inertial down position is indicate as $\boldsymbol{h}$. The angular rates are noted by **p** for roll rate, **q** for pitch rate, and **r** for yaw rate. **F** denotes the force generated by all UAV motors while **m** denotes the UAV mass.

The moments of inertia are represented by $\boldsymbol{Ixx}$ for the moment of inertia about the x-axis, $\boldsymbol{Iyy}$ for y-axis moment, and $\boldsymbol{Izz}$ for z-axis. Roll torque is indicated by $\boldsymbol{\tau\phi}$, $\boldsymbol{\tau\theta}$ for pitch torque, and $\boldsymbol{\tau\psi}$ yaw torque with $\boldsymbol{g}$ for the standard gravity constant (9.81 m/s^2). The state variables of an aircraft are shown in Figure 8. The velocities of an UAV are denoted by **u** for forward velocity, **v** for lateral velocity, and **w** for vertical velocity. Figure 9 shows the torque directions and motor positions of an UAV as viewed from the top of the UAV. Figure 10 shows the definition of forces acting on the UAV.

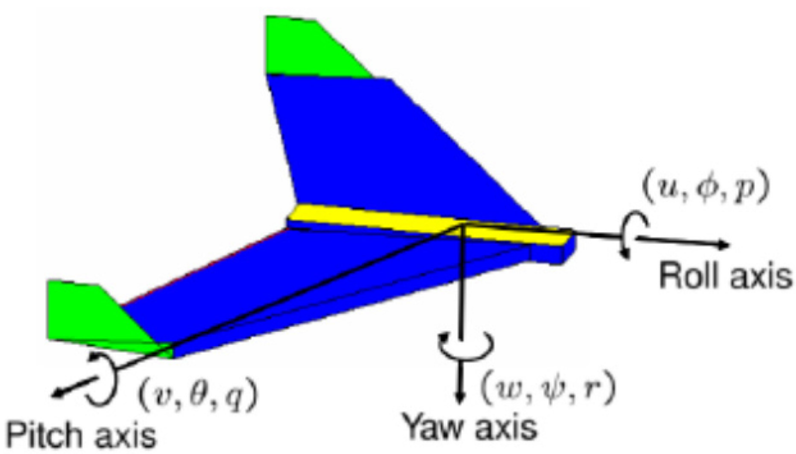

Figure 8: Schematic View if the State Variables of an Aircraft.

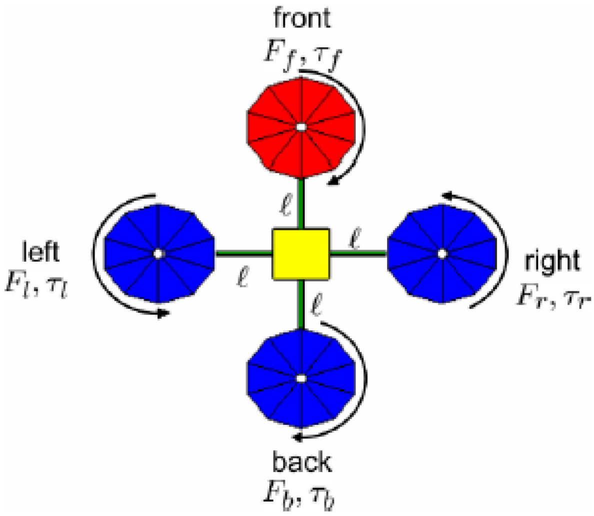

Figure 9: Top View of a Quadrotor Denoting the Torque Directions and the Motor Positions.

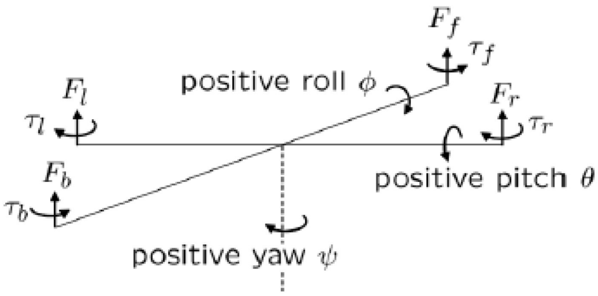

Figure 10: Definition of Forces Acting on the Quadrotor.

The influence of propeller and blade aerodynamics are complicated and difficult to model, and only becomes significant at high velocities; thus, they are excluded from the model.

The dynamic equations can then be simplified into [26]:

$$\ddot{p}_n = \frac{F}{m}(-\cos\phi\sin\theta\cos\psi - \sin\phi\sin\psi)$$
$$\ddot{p}_e = \frac{F}{m}(-\cos\phi\sin\theta\sin\psi + \sin\phi\cos\psi)$$
$$\ddot{h} = g - \frac{F}{m}(\cos\phi\cos\theta)$$
$$\ddot{\phi} = \frac{1}{I_{xx}}\tau_\phi$$
$$\ddot{\theta} = \frac{1}{I_{yy}}\tau_\theta$$
$$\ddot{\psi} = \frac{1}{I_{zz}}\tau_\psi$$

6.0 LSS DETECTABILITY

6.1 Phenomena

Several phenomena can be used to detect and identify a LSS UAS. These include the following [22]:

- Reflectance of UV/Visible/NIR/SWIR/MWIR/LWIR photons;
- Reflectance of a particular photon polarization state;
- Radar reflectance;
- Acoustic emission;
- Electromagnetic emission from on-board radios, WiFi, altimeters, radar, or other communication links; and
- Induced magnetic field.

These phenomena are associated with a wide range of technologies:

- Passive visible imaging (UV, visible, NIR);
- Passive thermal imaging (SWIR, MWIR, LWIR);
- Active Time of Flight systems (LIDAR, range gate imaging, etc);
- Acoustic-based sensors;
- RF emission;
- Radar-based systems;
- Magnetic detection systems; and
- Human intelligence.

6.2 Detectability

The LSS detection capabilities are generally affiliated with one or more of the above attributes.

Generally, from a detectability perspective, it is possible to group the LSS UAS into three main groups [1]:

- Glider UAS made with radar transparent materials – Very small radar cross section, very low thermal signature, potentially camouflaged to visible cameras, low/no acoustic signature, very few metal components.
- Quadcopter UAS – Small radar cross section, commercially prevalent, requires limited and easily acquired knowledge to pilot, mild acoustic signature, newest quadcopter UAS can be automated with limited to no human control.
- Jet turbine-based UAS – Small radar cross section, can reach extremely high speeds (compressed response timeline), components readily available for purchase online.

The ability to detect these UAS with conventional technologies is summarised in Figure 11, where green, yellow, and red indicators represent good, mild, and poor detection performance, respectively. The lack of green indicators for all UAS types is supported by the findings of the NATO study [8], namely that multiple detection technologies must be integrated or fused into a single detection/classification architecture to ensure higher probability of detection.

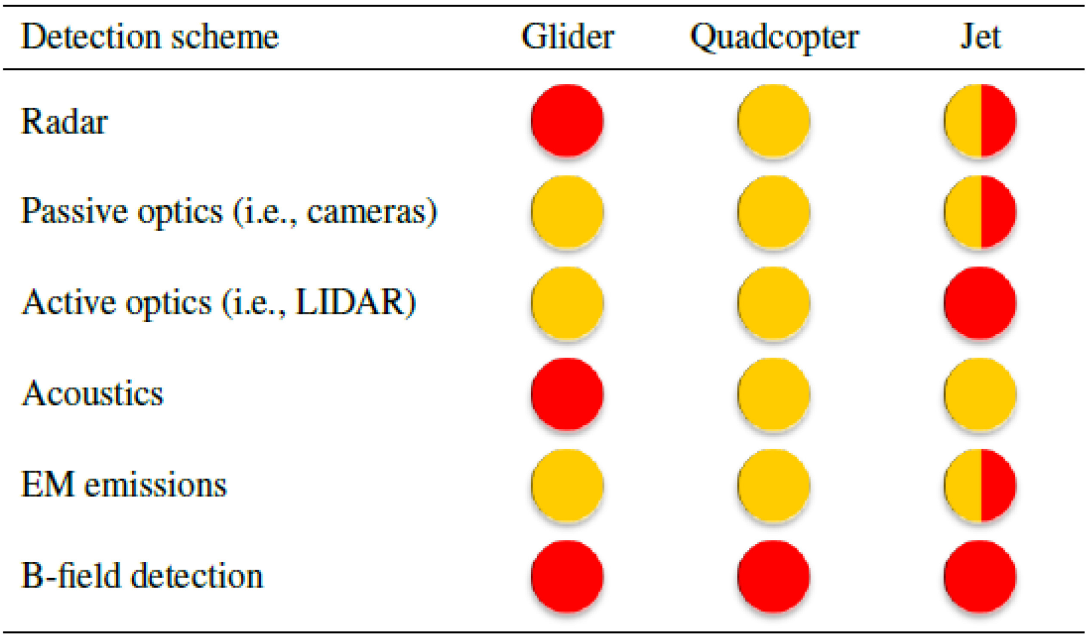

Figure 11: Ability to Detect Typical UAS Types Based on Conventional Sensors.

Consequently, to model the signature against different types of detectors, and since it has been asserted that multiple sensors are required for the capability, and the probability, of detecting such small objects, it is necessary to consider the parameters described in Section 4.

6.3 Study Weakness

As anticipated in Section 1, the Study Group faced a problem of lack of expertise within the Group due to the very specific specialisation on the subject.

The Group, unanimously, decide to organise a new activity dealing specifically to get information on sUAS detectability and signature modelling and characterisation.

From this perspective, the MSG-SET-183 Specialists' Meeting on "Drone Detectability: Modelling the Relevant Signature" was organised [4], [5], [6].

6.4 Specialists' Meeting Outcomes

The objectives of this Specialists' Meeting were to understand the requirements that have to be met by a drone detection system with respect to the drone characteristics that constitute the sUAS signature.

The Specialists' Meeting considered four themed Sessions as described below [5], [6]:

1) **Current Detection Technologies – Experiences and Challenges with Modelling sUAS Signatures**

   Countering small Unmanned Aerial Systems is not a new challenge and detection solutions are already available on the defence market. Experiences from the development of these systems should give an insight into the complexity of sUAS characteristics and the challenges arising when defining the relevant signatures of these systems to enable reliable detection methods.

2) **Recent Developments and Future Threats – Anticipated Challenges for Modelling sUAS Signatures**

   Technology is developing rapidly, in many cases, faster than the defence industry or NATO can react. Therefore, traditional signatures may be inappropriate to support detection of future sUAS. Furthermore, new technologies, such as the fifth generation cellular networks, may allow for concealing the signature of electromagnetic emissions of the Command and Control link inside the network.

3) **Modelling the Relevant Signatures for 'Traditional' Detection Methods**

   We can assume that detection methods utilizing 'traditional' signatures such as, e.g., radar, EO/IR, or acoustics will still be relevant in the future. UAS, no matter how small, will still have to obey the laws of physics and emit traceable signatures in the electromagnetic spectrum. Therefore, it is important to identify those parts of the spectrum (EM, RF, Acoustic, Thermal, etc) where sUAS provide their most prominent signatures.

4) **New Approaches for Modelling the Relevant Signatures to Enable Future Detection Methods**

   Currently fielded detection methods for sUAS may reach their limits if new technologies are applied. Future sUAS may be even smaller, faster and less visible than today. Autonomy and Artificial Intelligence may significantly reduce or eliminate active transmissions from and to the air vehicle. Hence, signatures of sUAS may be more difficult to track and even incapable on their own to track reliably.

The Specialists' Meeting, although in a virtual format, facilitated the information exchange on sUAS signature characterisation and related modelling through presentations on most of the above-mentioned topics from research and innovation points of view, including theoretical studies, and trials and experimentation, based on research combined with modelling activities.

Many suggestions concerned improvement on current studies and suggested areas for further NATO research activities. Reinforcing links with military bodies in NATO was highlighted as a way to improve the capability to meet the identified requirements, with the objective of increasing the capability of modelling for testing and evaluating, especially with respect to the new generation of Counter sUAS systems. In this way future research would lead to developing and deploying appropriate defensive measures, in terms of the detection, classification, tracking and neutralisation of current and future sUAS threats in a cost-effective manner.

In particular, it has been stated that the possibility of modelling radar signatures, as well as the acoustic signature, for different drones, radars, and scenarios would complement experimental data and help the development of tracking, classification, and situational awareness algorithms. Furthermore, the usefulness of radar scenarios simulation and their potential use for target modelling and feature extraction has been confirmed. Model assessments are usually made by comparing the simulation of RCS of UAV and the measurements of such UAV in an anechoic chamber, also with the purpose of obtaining a robust classifier to predict UA class of real experimental radar track data.

Nevertheless, a clear modelling of the drone signature with respect to its characteristics, both physical and dynamic, seems not easily feasible due to the complexity and variability of the drones on the market and their continuous enhancements.

7.0 CONCLUSIONS

The C-LSS context presents some unique challenges and opportunities to the Modelling and Simulation community. It allows for the:

- Incorporation of models of new and rapidly changing threat platforms with a wide range of flight dynamics;
- Production of simulations that allow the full range of new technologies to be exercised and evaluated in realistic environments; and
- Development of modelling and simulation of various operational situations to be exercised for planning and acquisition purposes.

To achieve the above objectives a robust parametric model of drones and sUAS would have been necessary.

The complexity and variability of the characteristics of sUAS makes it very difficult to accomplish the task of defining a parametric model suitable for use in a simulation system.

This is due both to the several parameters which characterise the drone itself, as described in Section 4, and the complexity of the flight dynamics equations able to take into consideration all the drone manoeuvrability capabilities and features, as described in Section 5.

Moreover, again the complexity and variability of the characteristics of sUAS do not allow the definition of a parametric model for assessing the relevant signatures, as explained in Section 6.

This means that, unfortunately, the objectives of the MSG-154 Study, as defined in the Technical Activity Description [3], cannot be successfully achieved.

From a practical point of view, it is still a valid option to use an already existing flight simulator software tool that can be used to simulate the flight responses of aircraft with a high degree of accuracy, also allowing the user to create any type of aerial vehicle. The limit of such a product is that the aircraft models are from a piloting point of view, that is just implementing an aerodynamic model, without taking into account the globality of parameters as defined in this Study, especially from detectability point of view. There are several examples of flight simulator software found in the fields of professional and videogame application, but they are not listed in this report in order to avoid any product endorsement.

8.0 RECOMMENDATIONS AND WAY AHEAD

Although the MSG-154 has not achieved its objectives, it has opened up the possibility of finding a way to model drones and sUAS with the purpose of using the models in a simulation system.

The most feasible approach, in the view of the MSG-154 Study Group, is to consider measurement campaigns in order to identify experimentally the incidence of drone characteristics in detectability and behaviour. This activity could be of interest to the NATO STO AVT Panel as a follow on to the AVT-296 RTG on “Rotorcraft Flight Simulation Model Fidelity Improvement and Assessment” with respect to sUAS [27].

Therefore, the MSG-154 recommends establishing a set of lookup tables in order to replace complex and unfeasible runtime computations with a simpler array indexing operation with respect to different drones’ parameters and characteristics. The tables may be pre-calculated and stored on the basis of the measurement and experimental campaigns.

Such tables could also help in identifying the impact that each parameter has on drone modelling, which could lead to a simpler model definition.

Moreover, the two tasks no longer addressed by the MSG-154 related to sUAS/LSS malicious behaviour and to tactics modelling for defining the Rules of Engagements (RoE) against the threat posed by the sUAS/LSS, should be taken into consideration for further studies.

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14. Abstract

The proliferation of Low, Slow, and Small (LSS) flying platforms brings with it a new and rapidly increasing threat to national defence and security agencies. Thus, defence systems must be designed to face such threats. Modern operational readiness is based on proper personnel training that is performed on high fidelity simulators. The aim of MSG-154 is to take into account the variety of commercially available LSS aerial vehicles and to define LSS models from different points of view so that models may be made available for those analysis and design aspects that relate to Counter LSS systems (both detection and neutralization,) and to operational training. The ability to cross correlate friendly nation LSS capabilities among member nations and to extend LSS to existing categorizations is considered to be both useful and beneficial.

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