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EN INFORMATIQUE

by

Nader SAMIR LABIB
Born on 13 August 1990 in Giza, Egypt

A DISTRIBUTED UNMANNED AERIAL VEHICLES TRAFFIC MANAGEMENT SYSTEM

Dissertation defence committee
Dr. Grégoire DANOY, Dissertation Supervisor
Research Scientist, Université du Luxembourg

Prof. Dr. Ulrich SORGER, Chairman
Professor, Université du Luxembourg

Prof. Dr. Frédéric GUINAND, Vice-Chairman
Professor, Université Le Havre Normandie

Dr. Jean-Philippe HUMBERT
Adjoint à la Direction, ILNAS

Dr. Matthias R. BRUST,
Research Scientist, Université du Luxembourg

Preface

Living in times of unprecedented technological evolution and transformation, what is considered interdisciplinary today may very well be a specialised domain tomorrow.

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Driven by my passion of not only to find out but to develop tools and how-to frameworks to facilitate future technology developments, what lies before you, in this dissertation, is the outcome of years of hard work, investigation and research.

While the majority of doctoral dissertations are highly specialised and focused works that push the boundary of one specific scientific field by extending, challenging and building on the work of those who came before them, adding a single brick to the tower of collective knowledge of mankind.
This is not like those dissertations. This work is intentionally broad to reach out to many audiences, however detailed and thorough enough for any reader with a background in computer science or aerospace engineering to utilise; and to standalone as a contribution worthy of the award of a doctoral degree.

Rather than standing atop the tower of any one specific domain, this manuscript serves more as a bridge among many academic and non-academic towers, offering an interdisciplinary, holistic and proactive approach to addressing inevitable future challenges fuelled by our rapid transition into a fully–connected digital and information era.

Specifically, this work integrates and brings together tools, techniques and concepts from aerospace engineering, computer science and technical standardisation to advance the fundamental understanding of digital trustworthiness and present a solution framework for the safe management of autonomous unmanned aerial vehicles.

This dissertation is an attempt to address some pressing questions that challenge one of the most promising technologies to date, like "are drones the future of the Internet of Things?", "are we ready for a sky full of drones?" and "how can we handle such unprecedented air traffic demands?"

Nader S. Labib

UNIVERSITY OF LUXEMBOURG

Abstract

Doctoral Programme in Computer Science and Computer Engineering
Interdisciplinary Centre for Security Reliability and Trust (SnT)

Doctor of Philosophy in Computer Science

A Distributed Unmanned Aerial Vehicles Traffic Management System

by Nader S. LABIB

The rapid adoption of Internet of Things (IoT) has encouraged the integration of new connected platforms such as Unmanned Aerial Vehicles (UAVs) to the ubiquitous network. UAVs promise a pragmatic solution to the limitations of existing terrestrial IoT infrastructure as well as they bring new means of delivering services through a wide range of applications ranging from monitoring and surveillance to on-demand last-mile delivery and people transport. Owning to their potential, UAVs are expected to soon dominate the low-altitude airspace over populated cities. This introduces new research challenges such as the safe management of UAVs operation under high traffic demands. In response to this, industry proposed a handful of constructs for UAV Traffic Management (UTM), however due to their centralised approaches, they will inevitably face limitations in scalability and resilience with predicted traffic demands and advancement in UAV autonomy.

In this context, the main objective of this work is to address the aforementioned problem by proposing a distributed UAV Traffic Management system (dUTM). This thesis, hence, investigates the validity of the above hypothesis by:

(i) showing the performance insufficiency of centralised systems due to their inadequacy in efficiently optimising large UAV traffic,

(ii) showing why a distributed system is favourable due to its characteristics of scalability and resilience,

(iii) proposing a novel dUTM framework consisting of an airspace structure model, information exchange model and a traffic optimisation model that rely on distributed methods and approaches to intelligently handle highly dynamic and challenging traffic conditions.

To this end, this manuscript contributes to scientific literature by proposing a novel way of structuring the uncontrolled, low-altitude airspace and introduces a model of the Class G airspace as a multi-weighted multilayer network of nodes and airways. Additionally the work presents a novel distributed multiobjective path planning algorithm incorporating a dynamic multi-criteria decision matrix allowing each UAV or agent to plan their path relying on local knowledge gained via digital stigmergy. The PhD thesis additionally contributes to existing state of the art by exploring the technical standardisation landscape and investigating synergies between research directions and standards developments, taking into consideration pressing inherit challenges of UAVs within IoT such as security, data protection and privacy.

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First and foremost, I would like to thank Prof. Pascal BOUVRY for giving me the opportunity to pursue my PhD within a truly inspiring and interdisciplinary team of scientists and researchers.

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Besides my supervisor, I would like to express my gratitude to my advisor Dr. Matthias R. BRUST not only for his insights and comments, but also for the hard question which encouraged me to deepen my research.

My sincere thanks also goes to the rest of my thesis committee for generously offering their time, support, guidance and good will throughout the preparation and review of this thesis.

I gratefully acknowledge the funding and support received from ILNAS and ANEC GIE and the great team of experts who gave me access to their facilities and provided me all required technical reports and standards. Without their support, it would have not been possible to conduct this research.

A very special thank you to my colleagues and in particular: Dr. Boonyarit CHANGAIVAL and Dr. Abdallah IBRAHIM for all their support throughout my PhD journey as well as a special thank you to Asst. Prof. Jedrzej MUSIAL and Dr. Johnatan E. PECERO for their encouragement, insights and support.

I would also like to say a heartfelt thank you to my family for always believing in me and encouraging me to follow my dreams.

Last but certainly not least, I would like to thank my wife, who has been by my side throughout this PhD, supporting and encouraging me, and without whom, I would not have been able to complete what I had started.

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List of Abbreviations

IoT	**I**nternet **o**f **T**hings
ICT	**I**nformation **C**ommunication **T**echnology
CAGR	**C**ompound **A**nnual **G**rowth **R**ate
SAREF	**S**mart **A**ppliances **REF**erence
RFID	**R**adio **F**requency **ID**entification
IIoT	**I**ndustrial **I**nternet **o**f **T**hings
WoT	**W**eb **o**f **T**hings
IoE	**I**nternet **o**f **E**verything
M2M	**M**achine to **M**achine
PII	**P**ersonally **I**dentifiable **I**nformation
IFC	**I**nformation **F**low **C**ontrol
SDO	**S**tandards **D**evelopment **O**rganisation
NSB	**N**ational **S**tandards **B**ody
ISO	**I**nterational **S**tandardisation **O**rganisation
ITU	The **I**nternational **T**elecommunication **U**nion
IEC	The **I**nternational **E**lectrotechnical **C**ommission
CEN	**E**uropean **C**ommittee for **S**tandardisation
CENELEC	European Committee for Electrotechnical Standardisation
ETSI	**E**uropean **T**elecommunications **S**tandards **I**nstitute
ENISA	European Union Agency for Cybersecurity
WG	**W**orking **G**roup
JTC	**J**oint **T**echnical **C**ommittee
TC	**T**echnical **C**ommittee
TS	**T**echnical **S**tandard
TR	**T**echnical **R**eport
DIS	**D**raft **I**nternational **S**tandard
FDIS	**F**inal **D**raft **I**nternational **S**tandard
GDPR	**G**eneral **D**ata **P**rotection **R**egulation
DPIA	**D**ata **P**rotection **I**mpact **A**ssessment
UAV	**U**nmanned **A**erial **V**ehicle

RPV	**R**emotely **P**iloted **V**ehicle
BVLOS	**B**eyond **V**isual **L**ine **O**f **S**ight
BS	**B**ase **S**tation
MS	**M**obile **S**tation
SDR	**S**oftware **D**efined **R**adio
KKT	**K**arush–**K**uhn–**T**ucker
D2D	**D**evice to **D**evice
UE	**U**ser **E**quipment
WSN	**W**ireless **S**ensor **N**etwork
SAR	**S**earch **a**nd **R**escue
AMO	**A**daptive **M**ulti-scale **O**ptimisation
NASA	The **N**ational **A**eronautics and **S**pace **A**dministration
ICAO	The **I**nternational **C**ivil **A**viation **O**rganization
EUOCAE	The **EU**ropean **O**rganisation for **C**ivil **A**viation **E**quipment
EASA	The **E**uropean Union **A**viation **S**afety **A**gency
UTM	**U**nmanned Aerial Vehicle **T**raffic **M**anagement
dUTM	**d**istributed **U**nmanned aerial vehicle **T**raffic **M**anagement
SCF	**S**afety **C**ritical **F**unction
SRF	**S**afety **R**elated **F**unction
OSF	**O**roperational **S**upport **F**unction
ATM	**A**ir **T**raffic **M**anagement
ATC	**A**ir **T**raffic **C**ontrol
FAA	**F**ederal **A**viation **A**uthority
CORUS	**C**oncept of **O**peration for Eu**R**opean **U**TM **S**ystems
AGL	**A**bove **G**round **L**evel
ADS-B	**A**utomatic **D**ependent **S**urveillance–**B**roadcast
IRF	**I**nstrument **F**light **R**ules
VRF	**V**isual **F**light **R**ules
NAS	**N**ational **A**irspace **S**ystem
MSL	**M**ean **S**ea **L**evel
FL	**F**light **L**evel
FIR	**F**light **I**nformation **R**egions
CD&R	**C**onflict **D**etection and **R**esolution
CL	**C**ontainment **L**imit
TSE	**T**otal **S**ystem **E**rror

FIMS	**F**light **I**nformation **M**anagement **S**ystem
WNR	**W**ireless **N**etworked **R**obot system
WSANs	**W**ireless **S**ensor **A**ctuator **N**etworks
U2U	**U**AV to **U**AV
U2I	**U**AV to **I**nfrastructure

NSGA	**N**on-dominated **S**orting **G**enetic **A**lgorithm
MCDM	**M**ulti **C**riteria **D**ecision **M**aking
WSM	**W**eighted **S**um **M**ethod
WPM	**W**eighted **P**roduct **M**ethod
AHP	**A**nalytic **H**ierarchy **P**rocess
rAHP	**r**evised **A**nalytic **H**ierarchy **P**rocess
CHP	**C**ognitive **H**ierarchy **P**rocess
ANP	**A**nalytic **N**etwork **P**rocess
TOPSIS	**T**echnique for **O**rder of **P**reference by **S**imilarity to **I**deal **S**olution
IACO	**I**nverted **A**nt **C**olony **O**ptimisation
GOS	**G**lobal **O**ffline **S**tatic
GPD	**G**lobal **P**robabilistic **D**ynamic
LPG	**L**ocal **P**heromone **G**uided
MOA*	**M**ulti**O**bjective **A**star
eLPG	**e**xtended **L**ocal **P**heromone **G**uided

SnT	Interdisciplinary Centre for **S**ecurity, Reliability a**n**d **T**rust
ILNAS	**I**nstitut **L**uxembourgeois de la **N**ormalisation, de l'**A**ccreditation, de la **S**ecurité et qualité des produits et services

To my family

Chapter 1

Introduction

1.1 Context

Smart Information Communication Technologies (smart ICT), supported by the modern computing paradigms that are capable of storing, processing and analysing large amounts and varieties of data, have fuelled an age of digital transformation and accelerated the growth of data-driven applications to unleash numerous opportunities for businesses, individuals and society at large [195].

Today, the much-discussed technologies of Internet of Things (IoT), one of the main pillars of Smart ICT, have given rise to a new generation of intelligent mobile robots as connected devices and platforms. The primary value of which lies in their autonomy when making informed decisions to determine an action without explicit instructions from an operator.

Further catalysed by the miniaturisation of low energy consumption sensors and the recent 5G developments, the autonomous mobile robotics industry is set to register some of its highest Compound Annual Growth Rates (CAGR) for the coming decade. The demand for these intelligent mobile robots is increasing enormously, owning to their flexible operational potential. Autonomous mobile robots have shed light on a wide array of applications that were previously deemed infeasible and while the majority of use-case scenarios are for ground applications, the recent few years have witnessed the emergence and evolution of aerial robotics.

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have emerged as one promising new domain in the aerospace market sector as smart mobile robots. With use-cases quickly expanding beyond military to more commercial applications, the global commercial UAV market is set to reach USD 46.4 billion in 2025 from a USD 17.8 billion in 2019, registering a CAGR of 20.5%. UAVs not only offer a new means of efficiently collecting and transmitting data, but also promise a pragmatic solution to IoT terrestrial infrastructure limitations [194]. UAVs in turn have encouraged the development of a vast array of value-added services, making the low altitude airspace the new valuable shared resources [302].

1.2 Motivation

As IoT continues to transform the aerospace sector, UAVs are one clear example that has witnessed great evolution over the recent few years as they have shifted from solely aerial vehicles to smart mobile IoT connected devices and platforms.

This technological evolution that led the rapid growth of the global commercial UAV market, translates to a rapid expansion in the number of UAVs expected to operate within a limited shared resource, the low altitude airspace. Estimated at 12.2 million in 2019, the number of UAVs is anticipated to surpass 18 million by 2025 [120], magnitudes higher than the global commercial aircraft fleet currently standing at 26 thousand [78], to put things in perspective.

As industries and governments continue to find new potential applications for UAVs, it becomes safe to envision a near future where the low altitude airspace is dominated by Unmanned Aerial Vehicles on missions ranging from regular aerial data collection to on-demand delivery, medical emergency intervention to more demanding applications requiring sophisticated beyond line-of-sight multi-UAV swarm operations.

This in turn introduces a new set of obstructing challenges that need to be addressed in order to realise the full potential of Unmanned Aerial Vehicles (UAVs).

1.2.1 Problem Statement and Thesis Objective

In order to fully exploit and realise the full commercial potential of UAVs without violating individuals right to security, privacy and data protection, authorities and society seek solutions to safely overview all traffic, operators and users.

One viable approach to addressing these challenges is through a dedicated Unmanned Aerial Vehicles Traffic Management (UTM) system [252], an infrastructure to complement conventional Air Traffic Management (ATM) by facilitating data exchange between the different stakeholders. However, the constructs that are currently proposed and underdevelopment are merely a temporary solution and will soon face limitations in handling the anticipated unprecedented traffic demands, due to their centralised ATM–comparable architectures.

Given the nature of operation of aerial robotics, Unmanned Aerial Vehicles introduce a new set of challenges due to their high mobility, energy constraints, payload and connectivity limitations let alone lack of internationally agreed upon technical standards and airspace structures. This in turn emphasises the need of developing new solutions that extend beyond the currently proposed models to ensure the safe operation, efficient management of UAV traffic and utilisation of an already convoluted shared low altitude airspace. In other words, the following gaps should be addressed:

- The low altitude airspace structure or the lack thereof. To this date, the low altitude airspace remains uncontrolled and unregulated. However, a mandatory first step towards a successful traffic system is to design and model the low altitude airspace as its structure will have a significant role in air traffic management [286].

- Scalable traffic optimisation solutions. Mobile robot path planning is an optimisation problem that has been well-addressed in literature over the past years. However, most of the approaches have mainly focused on 2-dimensional (2D) and 2.5-dimensional (2.5D) methods [252] which are suitable for ground or water surface mobile robots, while distributed approaches for highly mobile autonomous robots like unmanned aerial vehicles requiring 3-dimensional (3D) path planning, remain less explored.

- Trust and trustworthiness. The whole aviation operational system is built on the premise of trust. Pilots trust that traffic controllers would provide them with accurate information and warnings to avoid collisions and controllers expect that pilots would respect and comply with protocols, to give an example. However, for autonomous unmanned aviation there is no standardised or regulated definition of the concept of digital trust and trustworthiness which in turn poses many privacy and security challenges [256].

- Standardisation. Over the recent years, the research and standardisation communities have independently worked towards solving some of the aforementioned problems, exposing inconsistencies and gaps in their solutions [276].

To this end the main objective of this work is to address the aforementioned problems by proposing a distributed and thus scalable and more resilient Unmanned Aerial Vehicles Traffic Management system (dUTM), which is founded on (1) international technical standards, (2) IoT concepts and (3) relying on local decisions and ad-hoc U2X communications.

1.2.2 Research Questions

Given the hypothesis that an Unmanned Aerial Vehicle Traffic Management system (UTM) with distributed decision making allows for better scalability and resilience, the main goal of this manuscript is to investigate the validity of the hypothesis by: i) showing the performance insufficiency of centralised systems due to their inadequacy in efficiently optimising large UAV traffic, ii) showing why a distributed system is favourable due to its characteristics of scalability and resilience, iii) proposing a novel dUTM framework consisting of an airspace structure model, information exchange model and a traffic optimisation model that rely on distributed methods and approaches to intelligently handle highly dynamic and challenging traffic conditions.

In order to ensure a scientific methodological approach as well as for better structure, the manuscript aims to address the following questions, drawing from systematic approaches relying on both descriptive and experimental research methods for support.

- How can UAV traffic be modelled in the very low-altitude airspace?

- How can optimisation models be defined to encompass problem–specific constraints (3D mobility) and objectives such time and energy consumption?

- How can distributed UAV traffic behaviours be designed to benefit the global traffic system?

- What role can standardisation play in dUTM development and how can research and standards align to address obstructing challenges?

1.3 List of Contributions

The main objective of this work is to examine the aforementioned hypothesis by exploring the possibility of developing a dUTM that is capable of overcoming the limitations of existing state of the art systems and constructs. This subsection, therefore, outlines the main contributions of the PhD.

- A comprehensive literature study on IoT and UAVs research and technical standardisation state of the art highlighting i) how digitisation led the transformation of UAVs into smart connected devices and platforms; ii) the inherent challenges of security, data protection and privacy as UAVs become part of the ubiquitous network of connected things.
- An exhaustive study on state of the art UTM systems as well as a comparative analysis of existing constructs' architectures and functionalities.
- A novel structure for the uncontrolled very low-altitude airspace as a multi-weighted multilayer network of nodes and airways to serve as a foundation to addressing the complex problem of UAV traffic management.
- A novel dUTM generic information exchange framework incorporating new developments in aerial communications to accommodate for future autonomous flight planning.
- A new optimisation model encompassing problem-specific constraints (3D mobility) and conflicting multi-objectives drawing from the proposed architecture and airspace structure models. Complemented by a set of novel optimisation approaches to intelligently handle highly dynamic and challenging traffic conditions.
- Inclusion and adaptation of national, regional and international IoT, UAV and aerospace technical standards throughout all proposed models and architectures in the manuscript with the aim of aligning scientific research and technical standardisation.

1.4 Thesis Structure

The manuscript is organised as follows (c.f. Figure 1.1):

- **Part I** presents the essential basic notions required to read the dissertation. The notions include an overview of emerging smart Information Communication Technologies (Smart ICT) with emphasises on Internet of Things (IoT) in **Chapter 2** followed by an introduction to Unmanned Aerial Vehicles (UAVs) and their key technological developments in **Chapter 3**. These chapters of the manuscript comprise of a comprehensive literature study on IoT and UAVs research and technical standardisation state of the art, emphasising the role and implications of digital transformation of UAVs as well as investigate the inherent challenges of security, data protection and privacy as UAVs become part of the ubiquitous IoT network. Furthermore, in this context, Part I presents an interpretation of the concept of digital trust and derivation of a definition of trustworthiness in emerging digital technologies, as a first contribution.

- **Part II** presents the key contributions towards the envisioned fully distributed UAV traffic management systems (dUTM). **Chapter** 4 presents an exhaustive study on state of the art UTM systems as well as a comparative analysis of existing constructs' architectures and functionalities. The chapter highlights the main UTM concepts and functionalities and emphasises the role of airspace structure and information exchange models in the success of dUTM. **Chapter** 5 follows by devising a novel structure for the uncontrolled very low-altitude airspace as a multi-weighted multilayer network of nodes and airways to serve as a foundation to addressing the complex problem of UAV traffic management. Followed by an overview of flight information systems and a novel dUTM generic information exchange framework incorporating new developments in aerial communications in **Chapter** 6. **Chapter** 7 presents a new optimisation model encompassing problem-specific constraints such as UAV mobility as well as conflicting multi-objectives drawing from the proposed information and airspace models presented in the preceding chapters. This is then complemented by a set of novel optimisation approaches to intelligently handle highly dynamic and challenging traffic conditions.the traffic optimisation models and approaches used followed by a thorough description of the experimental simulations, results and discussions on findings in **Chapter** 8.

- **Part III** concludes the work by presenting a summery of contributions as well as conclusions, objections and perspectives for research and technical standardisation directions in **Chapter** 9.

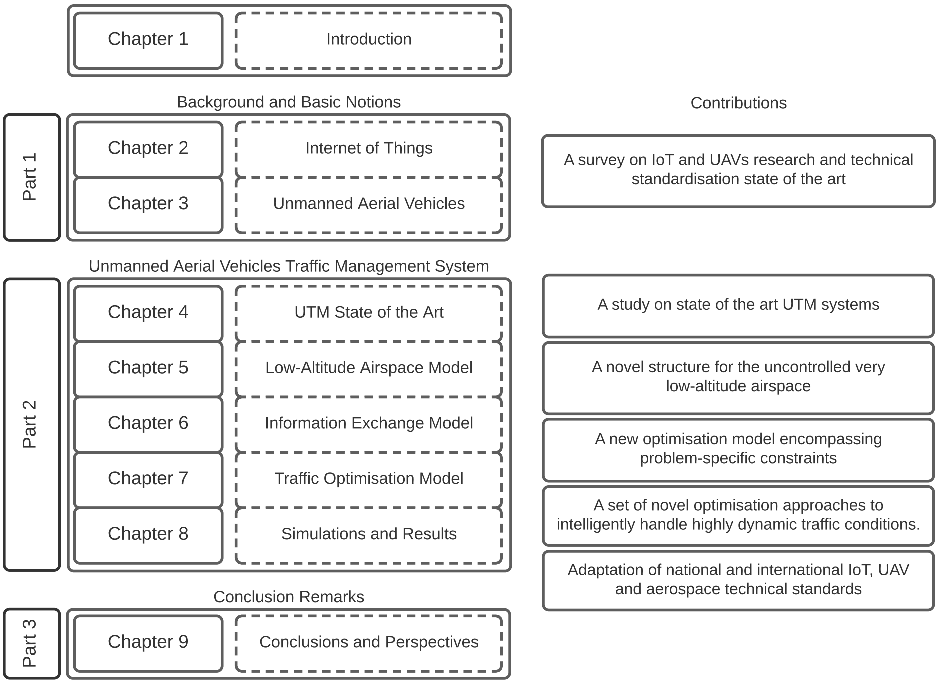


FIGURE 1.1: Graphical representation of the dissertation's structure.

End of Chapter 1

Part I

Background and Basic Notions

Chapter 2

Internet of Things (IoT)

2.1 Introduction

Broadly, the Internet of Things (IoT) refers to a network of uniquely addressable, interconnected objects, built on standard communication protocols whose point of convergence is the internet, hence enabling a wide array of services that were otherwise unfeasible to be realised [257]. IoT, nevertheless, has a distinct vision that extends inter-connectivity between both physical and virtual devices by envisioning an inter-connected world of things capable of providing services over the internet. In turn, these technologies have accelerated the growth of data-driven applications and catalysed the integration of new connected devices creating new value-added services in every market sector unleashing numerous opportunities for businesses, individuals and society at large [195].

The economic impacts of IoT are therefore undeniable, however, beyond the buzzword and notion of connected things, IoT is a complex technological paradigm and therefore introduces new challenges. The main goal of this chapter is therefore to provide a broad view of the technology landscape, highlighting its key notions. The structure is, hence, as follows, Section 2.2 presents a conceptual overview of IoT, its key definitions and building blocks followed by the technological landscape and its evolution and data model in Section 2.3. Section 2.4 follows on from there and delves into the concept of digital trust and state of the art of its main pillars of data protection, privacy and security. Section 2.5 then explores the technical standardisation with emphases on security data protection and privacy.

2.2 Conceptual Overview

While being a component of the next generation internet, IoT however has a distinct vision that extends inter-connectivity between both physical and virtual devices by envisioning an inter-connected world of things capable of providing services over the internet [119, 255].

In the context of the ubiquitous network of connected everything, this section gives an overview of the key definitions of IoT as well as the technology's basic building blocks.

2.2.1 Building Blocks

The Internet of Things (IoT) is complex paradigm that is often referred to as a system of systems. IoT is not a single technology, but rather an agglomeration of various technologies that work together in tandem.

The fundamental building block of the internet of Things (IoT) is the device commonly referred to as the "thing". Devices connect directly or indirectly to the internet and can be broadly categorised in two main groups, sensor and actuator, or a combination of both. Sensors are devices that gather information from the environment while actuators are devices that reach out and act on the world. These devices or things are connected using wireless and wired technologies to provide pervasive connectivity that is at the essence of IoT. Given the heterogeneity of devices, their limited storage and processing capabilities and the diversity of applications, middleware plays a key role in abstracting the functionalities and communication capability of devices. Middleware, not only connect components such as things, people and services, but also enable access to devices, ensure appropriate installation and behaviour of devices, furthermore, facilitate interoperability between local networks, cloud and other devices on the network. [257]

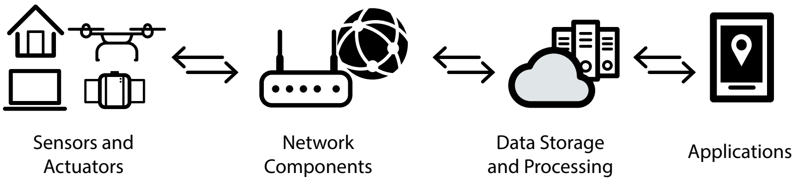


FIGURE 2.1: General concept of IoT building blocks.

While there is no single consensus on an IoT reference architecture, in literature, architecture layers vary between a three-layered to five-layered architectures an interested reader can find a survey of commonly used architectures in [198]. Throughout this work we refer to the IoT architecture presented in [257] consisting of four main layers, namely,

- the sensing and actuation layer which is lower–most layer and comprises of a wide range of devices that are referred to as things;
- the transmission and communication layer compromising of networking and transport capabilities;
- the storage and processing layer which includes components to store and process the generated data;
- finally, the application layer as the upper–most layer and it contains the IoT application user interfaces

Figure 2.1 illustrates the basic building blocks of IoT and their interconnectivity within a generic architecture [119].

2.2.2 Definitions

As mentioned above, the basic concept of IoT is the pervasive presence of a variety of objects, known as things, that through unique addressing schemes are able to interact with each other and cooperate to accomplish common goals [13].
Described as a single paradigm with a magnitude of visions [13], the definition of Internet of Things remains fuzzy. While such diversity in interpretation could be evidence to support the strong interest and the vivacity of debates on the promising technological paradigm, in many cases interested readers and researchers face challenges understanding what IoT really means. One reason for this ambiguity and fuzziness around the definition of IoT is a direct consequence of the term itself [77] which is syntactically composed of two terms. The first one pushes towards a network oriented vision of IoT, while the second one moves the focus on generic objects or ”things” to be integrated into a common framework [13]. Therefore, depending on the interest of the defining entity, IoT can be approached from, either, an internet-oriented or things-oriented perspective. To this end, the interested reader can find an exhaustive list of definitions of IoT in [204].

What is critical to keep in mind, however, is that the terms ”Internet” and ”Things”, when put together introduce a new level of disruptive innovation into today’s Information Communication Technologies’ world [272] forming the corner stone of what we refer to as Smart ICT. For the purpose of clarity, throughout the remainder of this work, we would refer to the Internet of Things (IoT) by its semantic meaning, used at the beginning of Chapter 2 as *”a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols”* [257].

2.3 Technical Landscape

While the Internet of Things could be part of today’s modern computing paradigms, one of the main pillars of Smart ICT, IoT’s origins and technical foundations are over decades old.
This section gives an overview of the technical landscape of IoT, highlighting the technology’s evolution and data model.

2.3.1 Evolution of IoT

Even though IoT has only recently become a buzzword and term used in almost every sector of the economy, the idea behind connected things dates back to the mid twentieth century. The actual term ”Internet of Things” is believed to have been coined by Kevin Ashton in [11] during his work at Procter & Gamble in 1999 at a time when the internet was emerging as a hyped technology. In a proposal to the company’s management, Ashton, who was working on supply chain optimisation at the time, used the term ”Internet of Things” when referring to his proposal of using Radio Frequency Identification system (RFID) [305] technology to connect and optimise supply–chains [11].
RFID refers to the automatic technology that allows computers and machines to identify objects, record metadata and possibly control individual targets using radio

frequencies. Therefore, by connecting RFID readers to internet terminals, the connected readers will be able to identify, track and monitor the objects attached with tags automatically in near-real-time and globally across the internet [136]. This, according to Ashton [11] gave rise to IoT.

Nevertheless, the concept of IoT did not really start gaining popularity until ten years later, specifically linked with 2010 Google's StreetView information leak [12] and the debate of whether or not Google had a strategy to index the internet and the physical world. During the same year, the government of China announced IoT as part of their five-year strategic plan and Gartner included it as a new emerging phenomenon in their hype cycle report [132]. The following three years continued to add to IoT's popularity. In 2012 topic of Europes biggest internet conference *LeWeb* was IoT, similarly, the Consumer Electronics Show (CES) held the same title in 2014. This mass market awareness was additionally emphasised in articles by *Forbes*, *Fast Company*, and *Wired*, the technology focused magazine giants.

Although it could be safe to consider RFID and later Machine to Machine communications (M2M) were the initial technologies or prerequisites of IoT [257], with the surge in mass market awareness new terms started appearing that added to the challenges discussed in subsection 2.2.2 above. Figure 2.2 clarifies the difference between the sometimes used interchangeably terminology by illustrating the reach and scope of each.

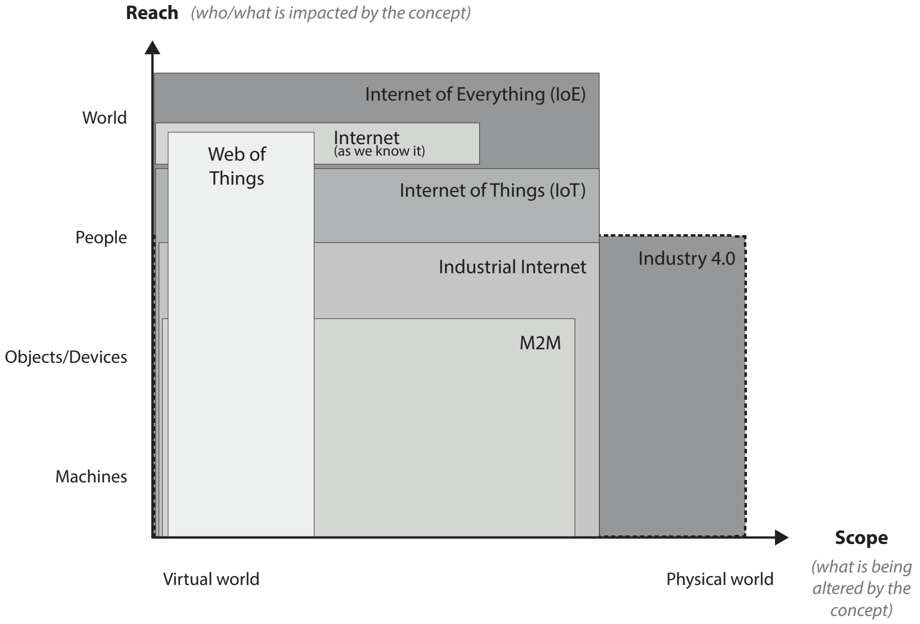


FIGURE 2.2: IoT concept disambiguation.

Machine to Machine (M2M) mostly used within the telecommunications industry, has been in use for more than a decade. Initially M2M refereed to one to one communication between machinery, however with today's advancement in mobile communications M2M expanded to a much wider range of devices. On the other hand, *Industrial Internet of Things (IIoT)* is a term that was strongly pushed by General Electric and goes beyond M2M by also including human interfaces. The term *Industry 4.0* that is strongly pushed by the German government is as limited as the industrial internet in reach as it only focuses on manufacturing environments. However, it has the largest scope of all the concepts. Industry 4.0 describes a set of concepts to drive the next industrial revolution. The term covers a larger scope than IIoT and M2M by including all kinds of connectivity concepts in the industrial context. Additionally, it goes further and includes real changes to the physical world around us such as 3D-printing technologies new augmented reality hardware. On the other side of the spectrum and in terms of reach, *internet* forms the basis of connecting people and *Web of Things (WoB)* builds on that concept solely focusing on software architectures, hence the scope of the term remains narrow in comparison to the rest. The *Internet of Everything (IoE)* a concept heavily supported by Cisco and is by far the largest in reach with aim to include all sorts of connections possible. It is however still very vague. Finally, *IoT* sits at the midpoint in terms of reach and scope, extending beyond the industrial concept towards a human-centred context.

IoT can therefore be seen as a system of systems where its scope and reach are continuously evolving as technologies advance. What is undeniable however is the direct correlation between the advancement in communication technologies and the volumes of data generated and exchanges.

2.3.2 Data Model

As previously highlighted in the above subsection 2.3.1, the amounts of data generated by IoT devices is increasing steadily with the advancement of communication technologies as well as the rapid and continuous introduction of new smart devices and platforms. This is illustrated in Figure 2.3, adopted from on ITU-T [131].

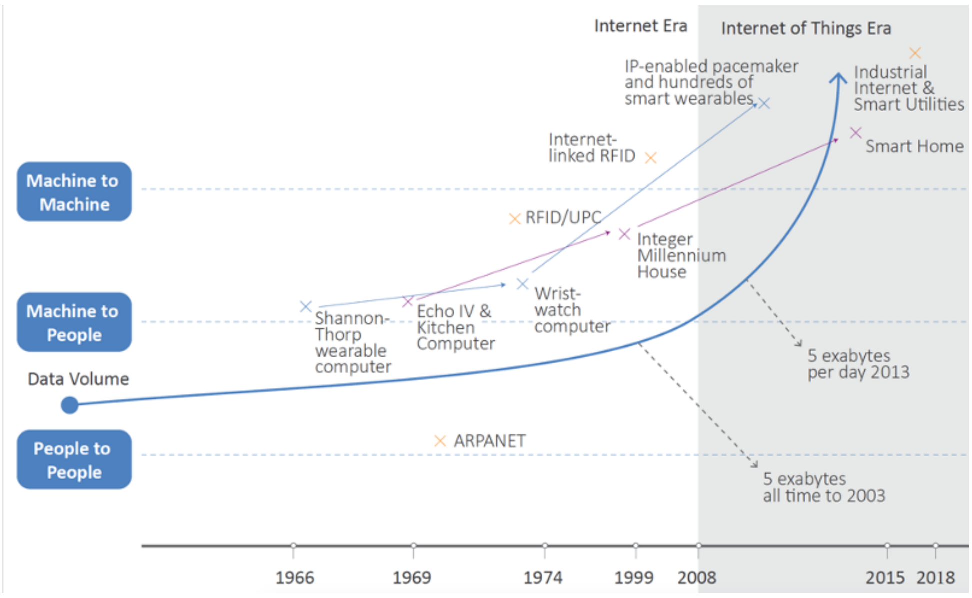


FIGURE 2.3: Data volume and communication technologies [131].

As the IoT market continues to evolve and take shape, the focus of solution providers shifts from connectivity to the increasingly important objective of handling the data that comes from connected things. In other words, that means finding ways to connect, manage, analyse and, eventually, share data among different entities. In addition to the novelty of large-scale and distributed data management, the characteristics of IoT as a heterogeneous system of systems introduce an additional layer of complexity. Such heterogeneity introduces new challenges in achieving interoperability with data whether across application silos, between partners in a supply chain or between vendors of interchangeable devices and sensors. A good data model would address these issues. In other words, an IoT data model would offer an approach which would allow to more efficiently describe, interpret, analyse and share data among heterogeneous IoT applications and devices.

Fortunately, literature proposes multiple data models as well as reference architectures that will be further elaborated in the following sections, however the interested reader can find a survey on the recent developments in [237]. Additionally, standardisation organisations present multiple domain-specific models some examples include Smart Appliances REFerence (SAREF) [43] provides a shared model for home appliances. Data models from the Open Geo-spatial Consortium [183] are more for Geo-sciences and environment domains. The Open Connectivity Foundation[72] specifies data models based on vertical industries such as automotive, healthcare, industrial and the smart home applications.

A collaborative approach to integrate and unify various data models is critical and necessary to work across IoT applications and platforms and achieving such unification requires cooperative efforts among standards development organisations. These efforts will be further discussed in section 2.5.

2.4 Digital Trust

With the emergence of new digital trends like the IoT, more industry actors and technical committees pursue research in utilising such technologies as they promise better and optimised management, improved energy efficiency and better quality living by facilitating a magnitude of value-added services. However, as communication, sensing and actuation become increasingly sophisticated, such promising data–driven IoT systems generate, process, and exchange larger amounts of data, some of which is privacy-sensitive and security–critical. The sustained increase in number of connected devices, catalysed by IoT, affirms the importance of addressing data protection, privacy and security challenges, as indices of trust, to achieve market acceptance [256].

2.4.1 Trust and Trustworthiness

The concepts of trust and trustworthiness are complex and have been a subject of considerable scholarly interest across different disciplines [95, 116]. However, when it comes to emerging digital technologies and in particular IoT, trust, better referred to as *digital* trust, and trustworthiness still need to be defined more precisely. As with the unprecedented number of connected devices and exponentially increasing data being collected within large-scale open distributed systems within the IoT ecosystem, they form the essential foundations, upon which ensuring the success and further development of the technology becomes possible [242].

Broadly, digital trust [116], adopted from the philosophical term of trust, consists of three main components, *a trusting entity, a trusted entity* and *a desired level of performance or deliverable* [95]; while trustworthiness refers to the property of a system offering a reliably constant level of confidentiality, integrity, availability and accuracy.

Hence, with focus on IoT, for the remainder of this study we describe trustworthiness in the IoT ecosystem according to the devised definition presented in our work [256] as:
"The affirmative confidence of an entity in the integrity of an IoT system, the sureness of the honesty and accuracy of devices and the reliability and confidentiality of digital information and networks on both levels of interaction; user-and-machine as well as machine-to-machine; where an entity could be a human user, digital device, IoT subsystem or software agent." [256]

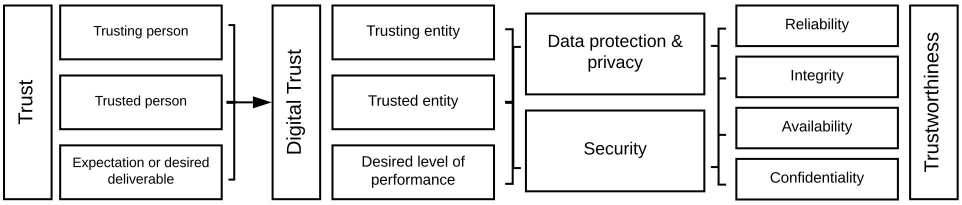


FIGURE 2.4: Digital trust and trustworthiness in IoT [256].

According to [220], *" a market's perception of trustworthiness depends on the indices of data protection measures and regulations, privacy and security;"* hence, in order to achieve an acceptable level of trustworthiness, data protection, privacy and security are major requirements to be addressed. Security is typically defined as the protection against unauthorised access, while data protection and privacy refer to a system's ability to protect sensitive Personally Identifiable Information (PII) [154].

To this end, Figure 2.4 adapts the illustration from [256] to summarise the above by exemplifying how the term trust has been transformed, by the emerging digital technologies, from its initial philosophical meaning described in [95] to digital trust, defined above. The figure then shows how the indices of data protection, privacy and security contribute to the property of a system being reliable, offering a constant level of integrity, availability and accuracy; hence, trustworthy.
In other words, within IoT, the trusting and trusted persons in [95] have transformed to trusting and trusted entities, respectively. These entities could be human users, digital devices, IoT subsystems or software agents. The figure then illustrates that through an acceptable level of data protection, privacy and security measures, trustworthiness could be achieved.

2.4.2 Data Protection, Privacy and Security

To achieve market acceptance, an acceptable level of trustworthiness has to be met and hence, addressing data protection, privacy and security needs becomes critical. This section explores research developments and state of the art in IoT data protection, privacy and security.

The IoT concept evolved rapidly over the past few years to become an umbrella–term for interconnected technologies, devices, objects as well as myriad services. However, due to this exponential boom and rapid market adoption, there is still no clear and common definition of the concept, even after several attempts by the research community. In [19] the authors emphasise the need of establishing a common ground for quickly emerging technologies. Nevertheless, the authors stress on the fact that it is not a trivial task and for being effective, it has to capture as many applicable vantage points as it possibly can.

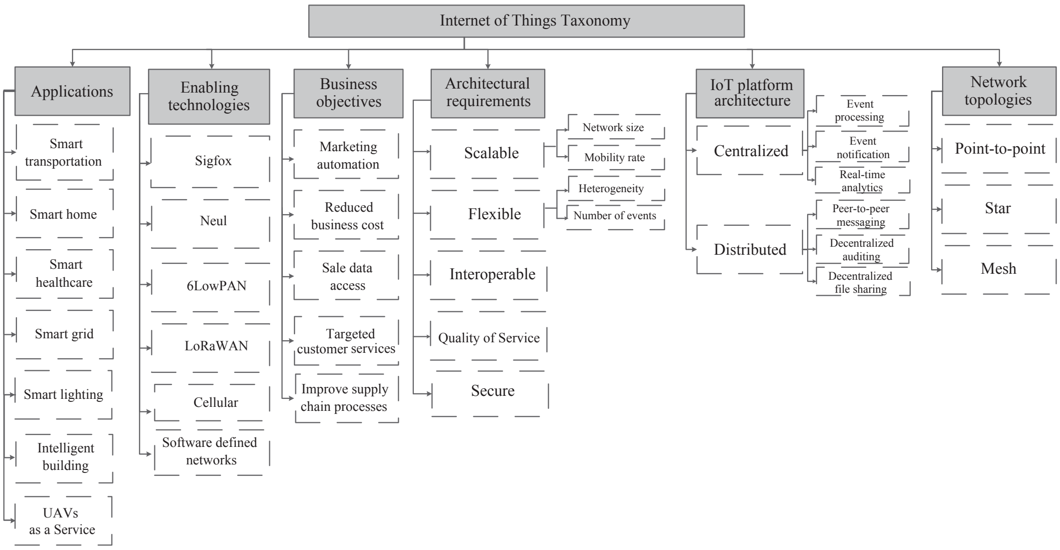


FIGURE 2.5: IoT taxonomy: applications, technologies, objectives, architectural requirements, platform and network topologies [323].

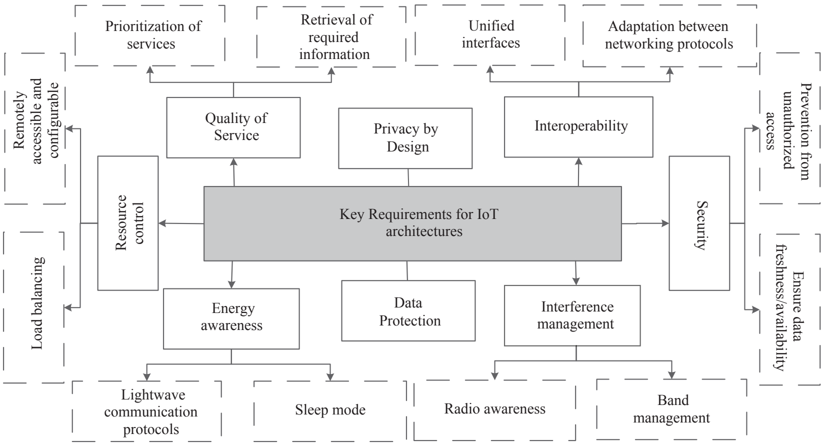


FIGURE 2.6: IoT architecture requirements [323].

A thorough analysis of most commonly used IoT concepts and IoT platforms can be found in [90]. In [323] the authors devise an IoT taxonomy based on parameters such as applications, enabling technologies, business objectives, architectural requirements, IoT platform architecture types, and network topologies as illustrated in Figure 2.5 (adopted from [323]). It can be deduced from this taxonomy that IoT is a system of systems with multiple enabling technologies and different communication protocols, adopted by different IoT entities for a wide range of application, hence making *interoperability* in IoT a challenge not trivial to address.

One viable solution to address interoperability challenges, concerned with data protection, privacy and security, is having a common *reference architecture*. This is further supported in [1] where the authors of the work emphasise that an IoT general reference architecture is essential to support the security and privacy of the network. To this end, literature provides several viable IoT architectures that could be used as a reference general model some are presented in [17, 306] ranging between 3–layer to 5–layer architectures as explained in [90] as well as in our work in [257]. However, despite of the number of layers or how they are divided, one common characteristic shared among all proposed architectures is that their devised layers comprise of the following components either as standalone layers or sub-components of a single one: i) *sensing and actuation component*, ii) *transmission and communication component*, iii) *processing and data storage component* and an iv) *application and interface component*. This is further explained in our work in [257]. In [323], the authors provide an illustration of IoT architecture requirements in terms of what any future IoT architecture should achieve. This is shown in Figure 2.6 as adopted from [323]. Furthermore, the authors argue that a reference architecture would not only support overcoming interoperability challenges, but would additionally help achieve market acceptance.

As subsection 2.4.1 explained the link between market acceptance and data protection, privacy and security, the following subsections aim to explore the aforementioned pillars and how they hinder establishing *trustworthiness* within the IoT ecosystem.

Data Protection and Privacy

IoT is a rapidly expanding with new entrants of physical and virtual objects and hence in contrast to conventional scenarios where users' actions are the main cause of privacy vulnerabilities, within the IoT ecosystem, devices or network nodes continuously collect individuals' data without their acknowledgement or consent [180].

In that context, ensuring privacy within the magnitude and variety of deployed IoT devices autonomously sensing and gathering private information is a pressing concern [257].
From physical and behavioural privacy, to location, information and communication privacy, our work in [257] shows that most challenges fall within the transportation and data handling layers in IoT.
One source of challenges highlighted in the aforementioned work is due to the interoperability within IoT systems. In other words, when one system interacts with other systems, each with their own privacy policies, inconsistencies arise. This in turn emphasises the importance of standardisation addressing IoT interoperability, data structure and exchange e.g., ISO/IEC 21823-1:2019 [124]. Literature provides some mechanisms and approaches to avoid inconsistencies and preserve privacy. One approach to address this is explained in [279], where the authors propose online consistency checking, notification and resolution schemes. Additionally, the work presented in [39] argues that mechanisms currently in use provide user–centric privacy, content oriented privacy or context oriented privacy. However, as mentioned above, within IoT networks, devices collect information autonomously and hence the need for new protocols is paramount. Moreover, the majority of the currently effective and recently put into force privacy regulations [76] mandate that users are always informed about how their data and information is managed and that no data should be collected without their consent. In turn making it crucial to develop new methods to identify nodes or devices that passively collect or have access to passively collected user identifiable information, which is a huge challenge in heterogeneous IoT networks as explained in [99].

To this end, Table 2.1 shows the a summary of privacy threats as adopted from [180] in which the state of the air current solutions in literature, potential challenges and future research directions are also discussed . The privacy threats presented in Table

Privacy	Threat	References
User	Surveillance networks	[21, 168, 246]
Content	Eavesdroppers when aggregating Infer query contents Behaviour prediction	[98, 225, 227]
Context	Link messages to sources Location leakage	[32, 137, 138]
Other	Data sharing Data combination	[137, 227, 245]

TABLE 2.1: Summary of IoT privacy challenges based on [180].

2.1 are categorised under i) user, ii) content and iii) context–oriented privacy as well as others as devised in [180].

Security

Security can generally be defined as protection against unauthorised access which is emphasised in [322] as the root of trust and backbone of data protection in IoT. Table 2.2 presents a summary of some main layer based attacks on IoT systems with their strategies as adopted from [216]. This is complemented by the work presented in [216] where the authors developed a taxonomy of IoT attacks divided under eight main categories; including, device property, location, strategy, access level, protocol based, information damage level, host based and communication stack protocol.

The security challenges within IoT are emphasised due to the current trends in devices' miniaturisation. This in turn come at the cost of limited computational power and energy, making most of today's security solutions unsuitable as they require heavyweight computations and large memory [257, 322]. Hence, lightweight security solutions for IoT devices is a current pressing research challenge, given the diverse technical nature of devices. Ideally, for a quick response, given the real-time or near real–time nature of a magnitude of IoT devices, the detection, countermeasures, and repairs must run in almost real-time, as part of a run-time self-healing architecture. However, healing can require reprogramming, in particular in cases where an unanticipated attack occurs. In such scenarios, healing instructions need to be securely delivered, with authentication and attestation, to the appropriate nodes and then the node's running programs need to be amended by the run–time architecture. This in turn emphasises that hardware and software are both crucial in establishing a secure architecture [279]. In order to provide authentication, access control and information flow control, as explained the remainder of this subsection.

Authentication: Authentication is the process of verifying the identity of a device or person. Within the IoT ecosystem, authentication is essential to allow the integration of different IoT devices that are deployed in different contexts [39]. Passwords are currently one example of commonly used IoT devices' user authentication mechanisms, however they are major source of concern due to weak passwords through which large DDoS attacks were recently facilitated. Another possible alternative is activity-based bio-metrics, however, IoT devices tend to be limited in input/output modules in turn constraining the authentication method [66, 68]. A more thorough survey on privacy can be found in [275], whereas for data protection, the authors in [291] offer a detailed analysis of IoT data protection considerations. Generally, IoT

Layer	Attacks	Methods/ Strategies
Physical	Jamming	Creates radio interference and exhaustion on IoT devices.
	Tampering	Creates compromised nodes.
Data Link	Collision	Simultaneously transmit two nodes of the same frequency.
	Exhaustion	By repetitive collision the nodes.
	Unfairness	Using above link layer attacks
Network	Spoofed information	Creates routing loops, extend or shortening sources routes.
	Selective forwarding	Choose what information that gathered before transmit it.
	Sinkhole	Monitoring, Redundancy, Authentication
	Sybil	Single node duplicates its node to be in multiple locations.
Transport	Flooding	Repeat request of new connection until the IoT system reach max level.
	De-synchronisation	Disruption of an existing connection.
Application	Attacks on reliability & Clone attack	Clock skewing, Selective message forwarding, Data aggregation distortion

TABLE 2.2: Layer–based IoT attacks and strategies.

adds more challenges to existing research when it comes to authentication and efficient key deployment and management as any cryptographic key generation and exchange should not cause any major overhead on IoT network nodes as explained in [321].

Access and Information Flow Control: Access control, as explained in [257] is a security technique that can be used to regulate what or who can view or use resources in a computing environment. This is achieved by limiting connections to computer networks, system files and data [110, 172]. However, the authors in [69] argue that access control is merely a gatekeeper and that it provides no further protection once code obtains access to sensitive resources. Nevertheless, complementing access control, information flow control (IFC) tracks how information propagates through the program during its execution to make sure that information is handled securely. IFC technique works by controlling how untrusted code uses access to sensitive resources. In [69], the work presented an analysed set of smart home platforms and concluded that the majority of current platforms rely solely on access control. Although IFC is not a new concept, the challenge lies in applying it meaningfully to a specific domain [110], an example of that would be FlowFence. As explained in [68], FlowFence is recent proposal for IoT frameworks that enable a data-flow-graph approach to IFC. IoT, however, extends current research challenges as the deployment and management of a variety of access control and IFC mechanisms is complicated in a heterogeneous IoT network. This is due to the fact that every IoT node may only support a limited number of access verification mechanisms which could vary from other objects connected to the same network node as emphasised in [207].

Challenges

To this end, it can be inferred from the above subsections that research and industry are developing methods and systems in an attempt to make IoT more secure and reliable. However, given the rapid pace at which the connected technologies are developing at as well as their diversity, there is a crucial need for harmonisation and standardisation. Such normalisation would avoid redundancies and potential conflicts as well as prevent future globalisation challenges such as a technology forklift update as the case was with telecommunication in the past.

2.5 IoT Technical Standardisation

When it comes to addressing large scale global harmonisation challenges as Section 2.4.2, technical standardisation plays a significant role. Broadly, technical standardisation is globally accepted for the qualitative and technical referential of repetitive processes, products and services. Standards are hence developed within organisations, referred to as Standardisation Development Organisations (SDOs), which bring together various stakeholders ranging from independent experts, representatives of organisations and industry to government administrations and National Standards Bodies (NSBs) to find consensus within a global regulatory and ethical framework [**wagle19**].

With focus on IoT technologies and relevant technical standardisation, this section gives an overview of the role of standardisation with regard to data protection, privacy and security as well as recent developments.

2.5.1 IoT Standards Overview and Developments

The majority of used internet protocols and standards are very complex for the power and processing constrained devices in IoT. As many of these devices are designed to run proprietary protocols, creating data silos. In the short run the vertical integration of sensors and business services will dominate IoT. The diverse communication protocols and the need for interoperability within the IoT ecosystems, motivates the need for establishing globally-harmonised regulations and internationally-agreed-upon technical standards to govern the technology's rapid advancements, as well as ensure a fair economy by encouraging market competition while lowering barriers to entry for newcomers [58].

Over the past few years, SDOs, on national, European and international levels, initiated dedicated WG in their TC with the aim to address challenges of data protection, privacy and security within the rapidly evolving IoT ecosystem. This was further catalysed by the new data protection regulations recently put into force, GDPR. Some of the relevant SDO technical standardisation committees and WGs currently active in IoT standards development, include *ISO/IEC JTC 1/SC 41* on Internet-of-Things and related technologies, *ISO/IEC JTC 1/SC 31* on automatic identification and data capture techniques, *ISO/IEC JTC 1/SC 32* on data management and interchange, *ISO/IEC JTC 1/SC 6* on telecommunications and information exchange between systems, *ISO/IEC JTC 1/SC 27* on Information security, cybersecurity and privacy protection [284], ETSI/TC SmartM2M on smart Machine-to-Machine communications [118] and *ETSI TS 103 645* [60] on cybersecurity for consumer IoT. Table 3 in [**wagle19**] presents a summary of SDOs and their involvement level in IoT standardisation, categorised under *terminology, interoperability, connectivity, security and privacy, trust, reliability and scalability, intelligence and others*.

With 20 published standards and 11 standards under development, *ISO/IEC JTC 1/SC 41*, like ITU-T and ETSI, is one of the more active technical subcommittees within IoT standardisation. *ISO/IEC JTC 1/SC 41* aims to stay up to date with current standardisation demands by forming liaisons with other committees within the SDOs. Out of the recently published standards, *ISO/IEC 21823-1:2019* [124] Part 1 provides an overview of interoperability as it applies to IoT systems and a framework for interoperability for IoT systems. This could be considered the foundation

A.Published

Technical Committee	Standard Reference	Title
ISO/IEC JTC 1	ISO/IEC 20924:2021	Internet of things (IoT) – Vocabulary
	ISO/IEC 30165:2021	Internet of things (IoT) – Real-time IoT framework
	ISO/IEC TR 30164:2020	Internet of things (IoT) – Edge computing
	ISO/IEC 30161:2020	Internet of things (IoT) – Requirements of IoT data exchange platform for various IoT services
	ISO/IEC 21823-2:2020	Internet of things (IoT) – Interoperability for IoT systems Part 2: Transport interoperability
	ISO/IEC 21823-1:2019	Internet of things (IoT) – Interoperability for IoT systems Part 1: Framework
	ISO/IEC 27701:2019	Extension to 27001/27002 – Guidelines for privacy information management
	ISO/IEC 30141:2018	Information technology – Internet of things (IoT) - IoT Reference Architecture
	ISO/IEC 27005:2018	Information technology – Security techniques – Information security risk management
	ISO/IEC 29134:2017	Information technology – Security techniques – Guidelines for privacy impact assessment
	ISO/IEC TR 22417:2017	Information technology – Internet of things (IoT) - IoT use cases
	ISO/IEC 29161:2016	Information technology – Data structure - Unique identification for the Internet of Things
ETSI	ETSI TS 103 645 V1.1.1 (02/2019)	Cyber Security for Consumer Internet of Things
	ETSI TS 103 458 v1.1.1 (06/2018)	Application of Attribute Based Encryption for PII and personal data protection on IoT devices
	ETSI TR 103 376 (10/2016)	SmartM2M; IoT LSP use cases and standards gap
ITU-T	ITU-T X.1361 (09/2018)	Security framework for the Internet of things based on the gateway model environments
	ITU-T X.1362 (03/2017)	Simple encryption procedure for Internet of Things (IoT) environments
	ITU-T Y.4115 (04/2017)	Reference architecture for IoT device capability exposure
	ITU-T Y.4455 (10/2017)	Reference architecture for Internet of things network service capability exposure

TABLE 2.3: Example of some published IoT technical standards.

B. Underdevelopment

Technical Committee	Standard Reference	Title
ISO/IEC JTC 1	ISO/IEC 27030	Information technology – Security techniques – Guidelines for security & privacy in IoT
	ISO/IEC 30147	Methodology for implementing & maintaining trustworthiness of IoT systems & services
	ISO/IEC 30149	Internet of things (IoT)–Trustworthiness framework

TABLE 2.4: Example of some underdevelopment IoT technical standards.

on which the second part, *ISO/IEC 21823-2* [125] on Interoperability for IoT Systems - Part 2: Transport interoperability and the third part *ISO/IEC 21823-3* [126] on Interoperability for IoT Systems - Part 3: Semantic interoperability are based. Both, the second and third parts of the interoperability standard are currently under development. Table 2.3 and Table 2.4 mention some of the recently published and under-development standards addressing IoT terminology, architecture and interoperability; for a more exhaustive list, the reader can refer to [117, 257, 284].

The GDPR requires organisations to undertake a DPIA before any new application is launched to minimise or yet restrict data breaches. In order to comply with such regulation, ISO offers *ISO/IEC 29134:2017* [128] which complements *ISO/IEC 27005:2018* [127] on information security risk management, by offering guidelines for privacy impact assessment. Additionally, the standards *ISO/IEC 20924:2018* on IoT terminology [123] and *ISO/IEC 30141:2018* [129] on IoT reference architecture that were published end of 2018 are currently under update to accommodate the rapid evolution of IoT.

From a European perspective, to address and support the envisioned digital single market [63] motivated by data-driven economic strategies [195], the European Telecommunications Standards Institute (ETSI) [276] is more focused on data protection and privacy aspects of the IoT technology. Less than one month after the General Data Protection Regulation (GDPR) came to force in May 2018, ETSI published *ETSI TS 103 458 v1.1.1* on application of attribute based encryption for Personally Identifying Information (PII) and personal data protection on IoT devices [59]. ETSI's efforts further supported *ITU-T X.1362* [131] that was published a year prior.

Moreover, the standardisation landscape shows consensus on the direction of their

work with all of ISO, IEC, ETSI and ITU-T currently developing standards for trustworthiness, data exchange and interoperability (c.f. Table 2.3). Additionally, the contributions within the delegates and National Standards Bodies (NSB) within these SDOs shows the diversity in the economic actors involved. This supports the argument made in [307] where the authors conclude that as more economic actors realise the importance of data protection and privacy in achieving this desired level of trustworthiness, the more they support and encourage *multi-mode* standardisation; where research organisations, industries, governments and SDOs contribute to the common challenges in securing IoT and protecting users' information [256].
Additionally, Annex A in the ENISA's recently published a report on IoT security and privacy standardisation gaps [121] offers the interested reader a clear overview of the recent standards in support of different category of requirements; namely, security by design; privacy by design; organisational, people and process measures; and technical measures.

End of Chapter 2

Chapter 3

Unmanned Aerial Vehicles (UAVs)

3.1 Introduction

As Internet of Things (IoT) continues to take industries by the storm, the aerospace sector undergoes transformation and witnesses rise to a new generation of intelligent aerial mobile robots. This digitisation within the aviation industry encouraged the shift of Unmanned Aerial Vehicles (UAVs) from solely being aircrafts to becoming smart mobile IoT connected devices and platforms with applications beyond the confinement of military use-cases.

The main goal of this chapter is therefore to provide an overview of the UAV technology landscape, highlighting its key definitions and notions as well as potential and challenges. The structure is, hence, as follows, Section 3.2 presents a conceptual overview of UAVs, its key definitions and history followed by the technological landscape and its evolution in Section 3.3. Section 3.4 explores UAVs as smart connected devices and platforms as well as the inherent challenges of UAVs within IoT. Then, Section 3.5 explores the technical standardisation efforts in addressing such challenges as well as highlighting key developments within that domain. Finally, Section 3.6 provides a concise summary and highlights key prospects and challenges.

3.2 Conceptual Overview

Over the recent years, UAVs emerged from solely military application scenarios to more commercial ones and have evolved as intelligent aerial mobile robots. Today UAVs can be considered as interconnected IoT devices and platforms that harness standard communication protocols to deliver new value-added services across myriad of application scenarios.

This section gives some key definitions of UAVs as well as an overview of the history of the technology.

3.2.1 Definitions

The term Unmanned Aerial Vehicles (UAV) came into use in the late twentieth century to include any robotic aircraft; however, the concept of robotic aircrafts dates back to the beginning of the nineteenth century and specifically before manned aviation ever took place. Since then the terms used to refer to aerial robots continuously changed and evolved over time as seen in Figure 3.1.

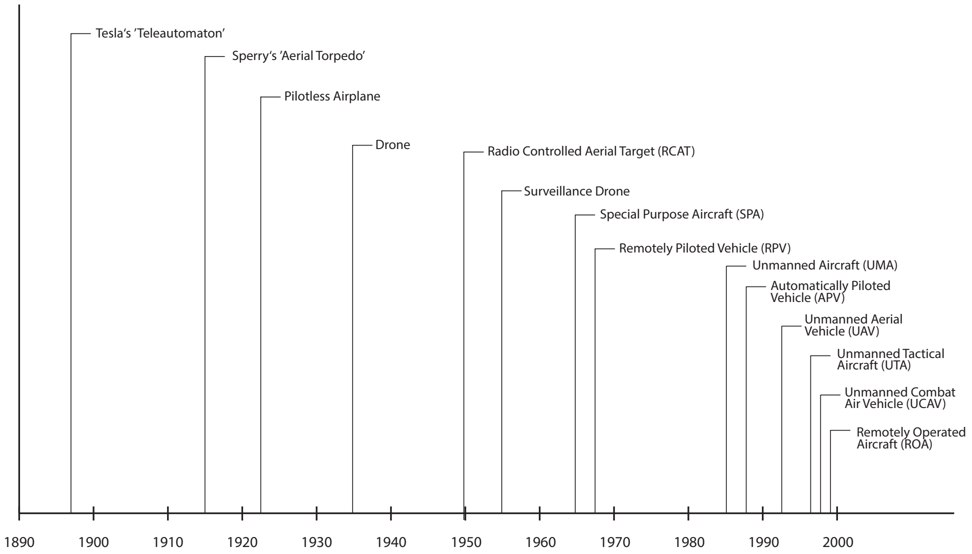


FIGURE 3.1: Chronology of terms used to refer to aerial robots [218].

It was not until after the Vietnam War that the term UAV came to replace Remotely Piloted Vehicle (RPV), a term previously used by the US military [81]. The US Department of Defence, therefore put out a definition of UAVs in which the term referred to any powered aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload. Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles [81]. The International Organisation of Standardisation (ISO) [130] on the other hand has a broader definition where the term UAV refers to any aircraft which is designed to be operated remotely or autonomously. For the purpose of clarity, throughout the remainder of this work, we would use the ISO definition to refer to UAVs.

3.2.2 Brief History of Unmanned Aviation

Unmanned aviation has its beginnings with the models built and flown by Sir George Cayley, John Stringfellow, Felix Du Temple, and other aviation pioneers as precursors to their attempts at manned flight in the first half of the twentieth century [218].

However, the idea of unmanned aviation can be linked back to Nikola Tesla's proposals and patent "*Method of and apparatus for controlling mechanism of moving vessels or vehicles*" [219]. Tesla not only deserves credit for founding the concept of unmanned aviation, but also for envisioning a future where UAVs would have unprecedented commercial applications. In an excerpt of his patent, Tesla describes some potential use-cases for his concept, *"The invention which I have described would prove useful in many ways. Vessels or vehicles of any suitable kind may be used for carrying letters, packages, provisions, instruments, objects or materials of any description, for establishing communication with inaccessible regions and for exploring conditions existing in the same... and for may other scientific, engineering and commercial purposes."* Tesla continues and describes how the realisation of UAVs would however first be for military applications. Nevertheless, it was only a decade later when first experiments took place, specifically after Elmer Ambrose Sperry [109], the father of modern day navigation, invented the gyro-compass [277]. Figure 3.2 illustrates a non-exhaustive list of some of the key dates and milestones related to unmanned aviation. To better show the evolution over time of both terminology and technology-related events, Figure 3.3 uses a common timeline to showcase and highlight the chronology of terms used to refer to aerial robots as well as the milestone events.

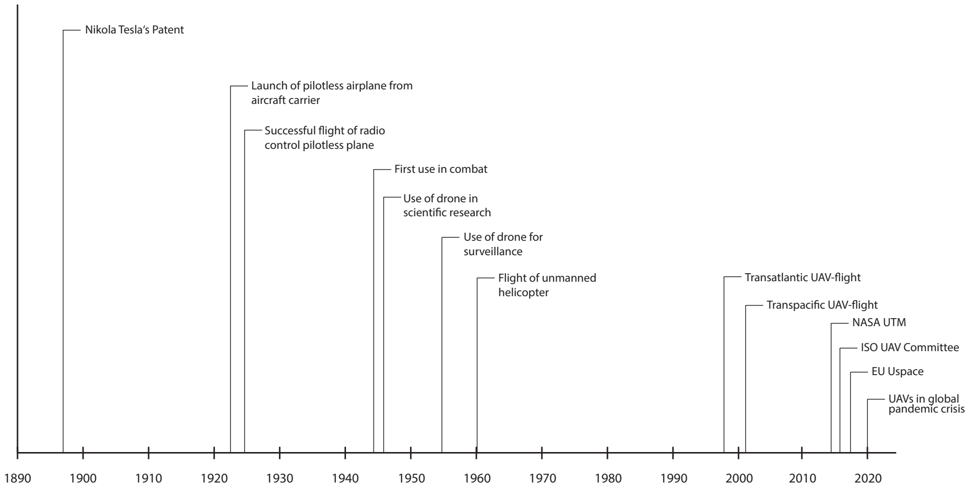


FIGURE 3.2: Timeline of key unmanned aviation milestones.

The most important reason for such delay was insufficient technology [218]. The development of unmanned aircrafts hinged on the confluence of four critical technologies which are further explored in section 3.3 and these include: flight propulsion, automatic stabilisation, remote control, and autonomous navigation.

3.3 Technical Landscape

Unmanned aerial vehicles are an evolution rather than a revolution [285]. While UAVs can be seen as part of our future connected smart cities, the origins of the technology are decades old.

This section gives an overview of the technical landscape of UAVs, highlighting the technology's building blocks and evolution.

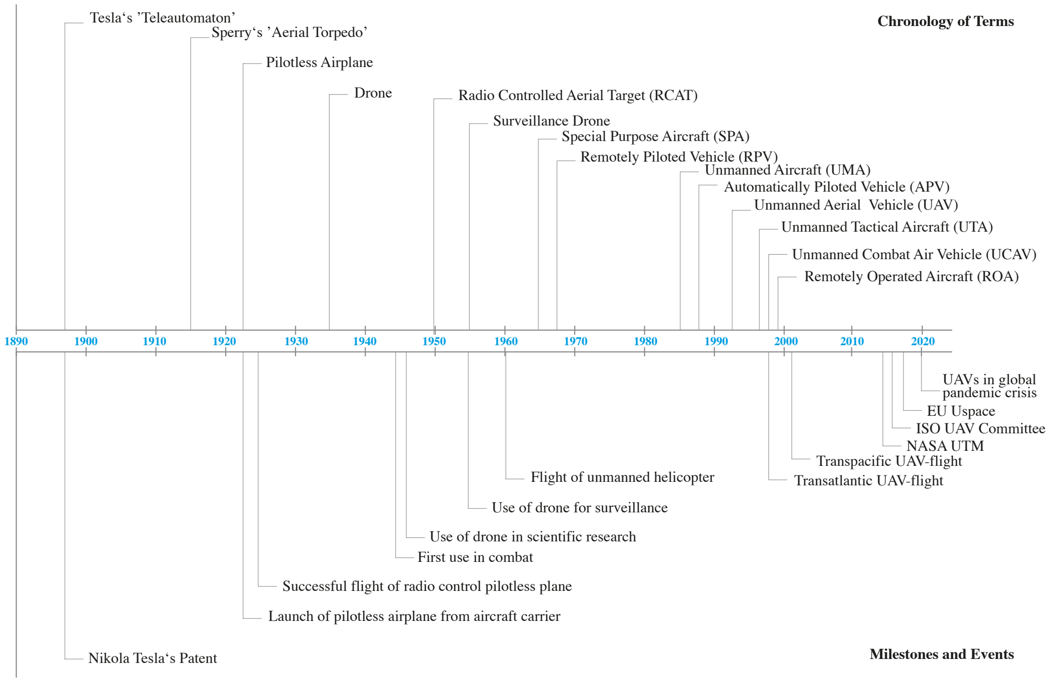


FIGURE 3.3: Chronology of terms used to refer to aerial robots adopted from [218] (**top**) key milestones and events (**bottom**).

3.3.1 Building Blocks

As explained in subsection 3.2.2 the early development of unmanned aerial vehicles critically depended on the convergence of four critical technologies flight propulsion, automatic stabilisation, remote control, and autonomous navigation. These technological challenges that hindered the development of UAVs for over a decade since the conception of the idea can broadly be translated to today's main UAV systems (c.f. Figure 3.4) namely, control, communication, navigation and propulsion.

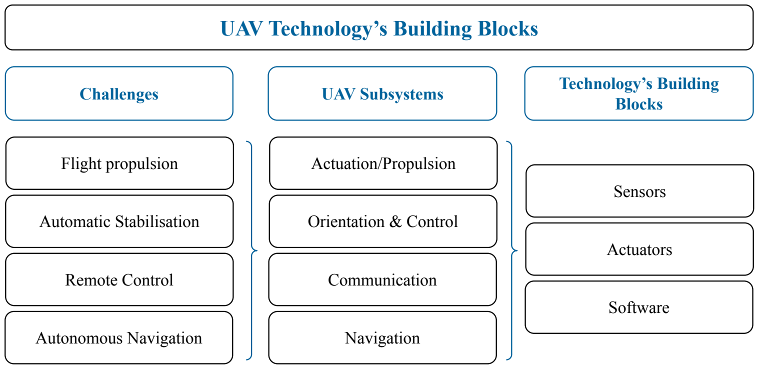


FIGURE 3.4: UAV technology's building blocks.

While a detailed explanations and thorough analysis of such systems falls out of scope of this work, the interested reader can find elaborate information in [64]. However, as seen in Figure 3.4, what is to our interest is that despite whether it is attitude and orientation control, communication and navigation or propulsion, they all share the same core technologies of sensors, actuators and power or energy storage and management. It is hence easier to comprehend the correlation between UAVs developments and sensors/actuators advancements.

3.3.2 Technical Evolution of UAVs

One of the main factors that led to the drastic change and development of UAVs, from the first successful radio controlled pilotless aircraft in 1924 (c.f. Figure 3.2) to the role UAVs play in fighting the global COVID-19 pandemic [300][164], is the great advancement in sensors technologies.
The evolution in sensory systems, introduction of intelligent wireless sensors networks, battery improvements have led to increase in reliability and drop in price which in turn contributed to moving the UAV development to the second and third stages of Malsov technology cycle [22] shown in Figure 3.5.

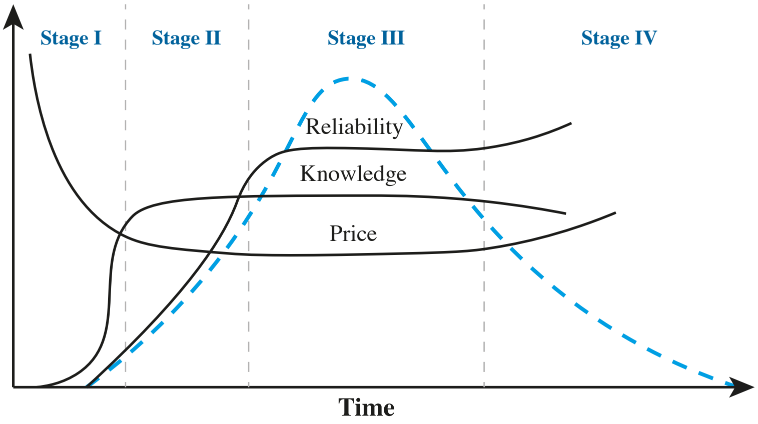


FIGURE 3.5: Maslov's technology cycle [22].

As new emerging computer paradigms continue to evolve, so does the autonomy capabilities of UAVs, relying on smarter algorithms and analysis. Ranging between 0 to 10 levels of autonomy [273] compiles an analysis of the various autonomy levels of UAVs, from a remotely piloted vehicle to a fully autonomous UAV capable of independent tactical and strategic mission planning.

3.4 State of the Art of UAVs in Internet of Things

Over the recent years, UAVs have quickly found their way into the Internet of Things, becoming promising connected devices and platforms to this ubiquitous network. Unmanned aerial vehicles offer new means of efficiently collecting and transmitting data as smart terminal devices capable of interacting with the physical world for a magnitude of IoT applications. Figure 3.6 (*right-hand side*) as adopted from [253], uses the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission's (IEC) generic architecture of Internet of Things first proposed in ISO/IEC 30141 [129] to illustrate some of the application scenarios, of UAVs within IoT, that will be later explored in detail.

This section provides a study of state of the art of some of the many use-cases of UAVs within the context of Internet of Things as i) part of the IoT infrastructure in subsection 3.4.1 and ii) a smart connected terminal devices and platforms in subsection 3.4.2. Furthermore, the section concludes by discussing the inherent limitations of UAVs within IoT with main focus on data protection, privacy and security in subsection 3.4.3, highlighting the role of technical standardisation in addressing such challenges.

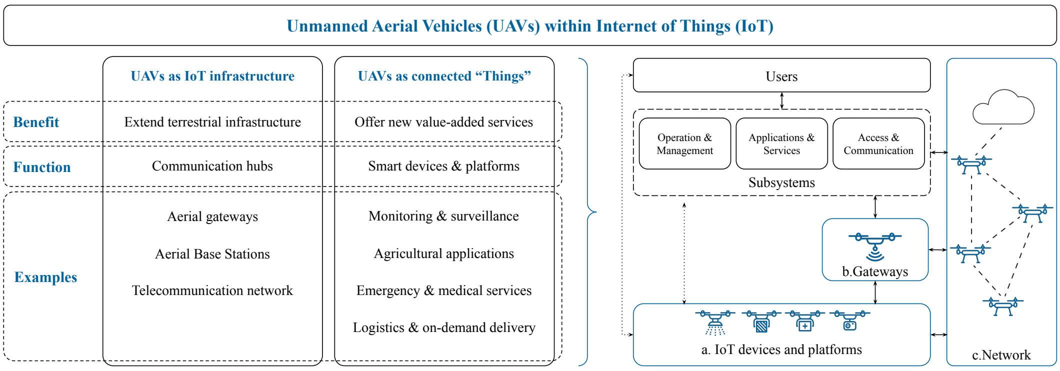


FIGURE 3.6: **Left:** Benefits, function and examples of UAVs as part of IoT infrastructure & UAVs as connected "Things". **Right:** Illustration of UAVs within the context of IoT as, (**a**) terminal IoT–devices that interact with the physical world; (**b**) aerial base stations & gateways; (**c**) telecommunication network connected to IoT cloud.

3.4.1 Pragmatic Solution to Terrestrial Infrastructure Limitations

Today, UAVs present a feasible dynamic and pragmatic extension to fixed IoT infrastructure, mainly in cases, when having terrestrial infrastructure would not be economically feasible or would not be sufficient to guarantee communication coverage with an acceptable level of quality [194]. Hence, making UAVs, when equipped with the appropriate telecommunication payload, a potential solution to overcoming such limitations by offering wider aerial–based communication coverage, improved availability and enhanced resilience as explored in [4, 328].

With the increasing demand for network coverage and the envisioned unprecedented loads on the current infrastructure, research has quickly found new uses for UAVs in telecommunications as aerial gateways and base stations to deliver emergency and on-demand telecommunication services.

Since the early 90s and research in the military context has investigated the use of UAVs for telecommunication scenarios. In [235] authors discuss the possibility of using UAVs to provide Beyond Line of Sight communications (BLOS) capabilities within an area of military operation without using scarce satellite resources.

Nowadays, with the introduction of commercial UAV applications, the scientific community, inspired by the ambitious idea announced by Google back in 2011 of providing internet using high–altitude balloons[142, 146], continuously researches innovative ways of utilising the use of UAVs in heterogeneous telecommunication networks.

Initially, most research focused on disaster relief and temporary communication infrastructure using UAVs. With advancement in communication technologies, the work presented in [182, 214] emphasises the importance of incorporating UAVs in multi-tier heterogeneous networks to extend network coverage and capacity in disaster-struck areas. To this end, literature provides multiple usecase scenarios, for example, in [86] authors use the 2011 great earthquake and tsunami in Japan as a use case to illustrate that communications infrastructure can be damaged during such disasters. The paper presents a UAV–based Software Defined Radio (SDR) platform that could be deployed rapidly for emergency communication use–cases. The authors explain that, in this scenario, UAVs act as aerial base-stations to provide cellular network coverage to users on ground within UAVs' vicinity. Additionally, the work in [57, 304, 331] discusses the interaction between UAVs and terrestrially deployed wireless sensors networks. The aforementioned papers emphasise the challenges related to energy management and UAV placement as well as provide possible solutions for maintaining a connected aerial mesh during handoff between UAVs taking into consideration UAV–specific, security and energy challenges.

Besides disaster relief and short–term, temporary emergency networks, the introduction of 5G and the growing communication demands of the vast heterogeneous IoT devices, call for new ways to utilise UAVs on continuous and regular basis within hybrid aerial–terrestrial network infrastructure [58, 211] to deliver IoT services [70, 210]. Recent work presented in [194] argues that the fifth generation of mobile communications would catalyse further applications where latency and quality of service cannot be compromised, the authors then present UAVs as a potential solution to foreseeable ground–based infrastructure limitations. Furthermore, the work in [269] presents supports the argument of the strain on cellular networks due to the inefficiency in handling the large traffic demands driven by the ever growing increase in users continuously requesting more data and services. The paper provides a viable solution utilising multiple UAVs to act as aerial-nodes connecting the macro and small cell tiers for improving coverage as well as increasing capacity. The authors investigate the problem of user demand–based UAV assignment over geographical areas subject to high traffic demands, formulating a neural-based cost function approach in which UAVs are matched with a specific geographical area. The results presented in in [269] illustrate that utilising multiple UAVs on one hand provides long range connectivity but also improve load balancing as well as traffic offload. The authors support their models by extensive simulations that demonstrate significant improvements of up to 38% and reduction in delays of up to 37.5% when compared to solely ground–based networks. This is further supported in [111] where the authors propose a novel hierarchical architecture of UAVs with multi–layer and distributed features in order to facilitate smooth integration of different mainstream UAVs into the next–generation wireless communication networks. The paper additionally unveils the critical comprehensive design trade-offs, in light of both communication and aerodynamic principles. The authors present empirical models and satellite measurement data to conduct numerical analysis of the meteorological impacts of UAV enabled, 5G high bands communications. Additional complementary research presented in [148] provides experimental review on ray-tracing simulation for a UAV–aided 5G networks where the authors main objective was to assess the usage of UAV in next-generation wireless networks. Moreover, a recent survey [226] emphasises the importance of UAVs in assisting 5G as well as beyond 5G (B5G) mobile networks. The authors provide comprehensive discussions the technologies and analyse use-cases to highlight pressing challenges and future research directions.

3.4.2 From an Aircraft to a Smart Connected Platform

Supported by the miniaturisation of sensors, actuators, processors and developments in wireless connectivity and energy storage systems as well as rapid advancements in IoT, UAVs are quickly finding many new uses in enhancing our everyday life as smart terminal devices. With the observed rate in development of innovative use–cases, it becomes safe to envision UAVs as important tools for people, businesses and governments alike. They will not only be used for disaster relief operations, but myriads of commercial services. From assisting in search and rescue missions, homeland security and boarder control to monitoring of traffic, construction sites to delivering medical supplies, to name a few examples.

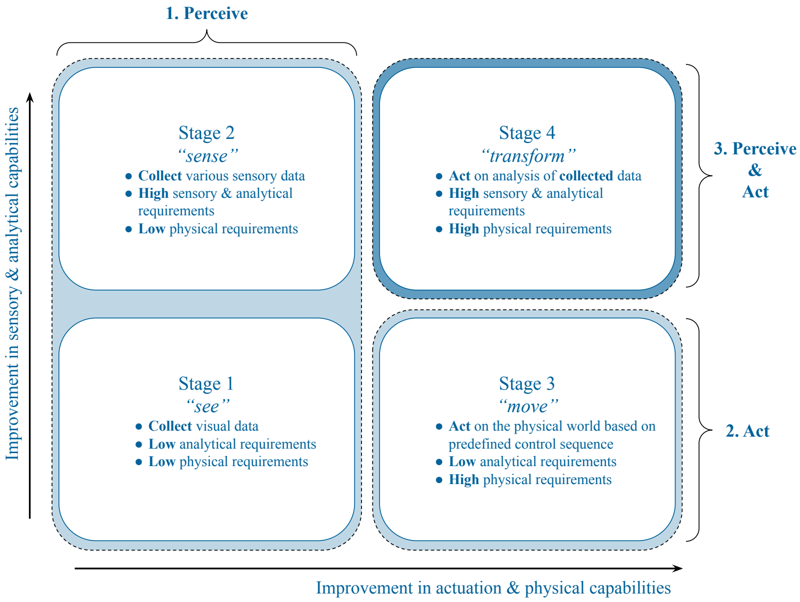


FIGURE 3.7: The three categories of UAV applications: *Perceive*, *Act*, *Perceive & Act*, illustrating the development from Stages 1–4 [184] governed by improvement in UAVs' sensing, actuation & analytical capabilities.

Given the expected wide usage of UAVs in different sectors and scenarios it becomes challenging to introduce all possible use cases; therefore, for the purpose of this work, we outline some predominant civil commercial applications found in scientific literature. Besides the classification presented in [184] of UAVs in manufacturing, there is no study, to the best of our knowledge, that presents a detailed taxonomy for commercial UAV applications. Building on the proposed classification of [184], we devise a categorisation of UAV applications into three broad categories based on the main role of the application, namely, *Perceive*, *Act*, *Perceive & Act*. Figure 3.7 presents the three categories of UAV applications and illustrates how Stages 1–4 representing "see", "sense", "move" and "transform" based on the classification of [184] respectively, develop in correlation to improvement in UAVs' sensing, actuation & analytical capabilities where *Stage 1* indicates basic data collection applications, while *Stage 4* indicates more complex applications where UAVs are able to perceive the physical environment and act based on a higher degree of autonomy.

In this context, this section explores each of the three categories then outlines some of the predominant applications in scientific literature followed by a summary in Table 3.1.

1. **Perceive:** applications where the main objective is data collection and perceiving the physical world. Such applications cover systematic, continual, and active or passive observation of places, things, persons or processes or in addition to use–cases consisting of targeted monitoring of activities for specific

evidence of faults, crimes or other wrongdoing. This category includes Stage 1 and 2 in Figure 3.7, where the former includes applications where the UAV does not require high analytical and computational capability while the latter requires UAVs to be able to collect and analyse multiple sensory data types. Some examples falling under this category include:

   (a) Asset and Traffic Monitoring
   (b) Persons and Crowd Monitoring
   (c) Environmental Monitoring
   (d) Agricultural Monitoring
   (e) Security and Surveillance
   (f) Infrastructure Inspection
   (g) Search and Rescue

2. **Act:** applications where the main objective is acting upon the physical world. Such applications compromise of logistics and supply activities. This category includes Stage 3 in Figure 3.7 requiring high actuation and physical capabilities but not necessarily high analytical and computational capabilities. for example:

   (a) Logistics and On-demand Delivery
   (b) Emergency and Medical Services

3. **Perceive & Act:** hybrid applications requiring higher degree of autonomy where UAVs are able to perceive their environment and act based on informed decisions. This category includes Stage 4 in Figure 3.7. Applications falling under this domain, while limited in comparison to previous categories, compromise of demanding application scenarios, for example:

   (a) Autonomous Urban Mobility
   (b) Detect and Extract

Asset and Traffic Monitoring

With regard to asset and traffic monitoring, an interesting review on the subject focusing on advantages and disadvantages of main methods found in scientific literature can be found in [143] and [147]. In these reviews, applications on traffic monitoring are organised thematically identifying the novelty and state-of-the-art. One of the first projects - WITAS [50, 222] was dedicated to the development of a fully autonomous UAV able to navigate at different altitudes and conduct several tasks including identifying, tracking and monitoring specific vehicles and assets. In [205, 270] the authors discuss the potential of collecting traffic data from aerial video footage; several key parameters were able to be extracted, according to the study, including car traffic densities, travel times, turning counts and queue lengths. Another more recent work [221] investigated the use of UAVs for asset and traffic monitoring applications by proposing and testing a complete traffic monitoring system using rotary-wing UAVs equipped with on-board cameras. The authors use video and data processing algorithms to detect vehicles based on the Haar cascade model. The results obtained conclude that the designed system can monitor traffic with high accuracy and flexibility. This complements the argument presented in [107] where the authors highlight the limitations of stationary ground-based traffic information collection methods and propose an alternative aerial traffic monitoring system using autonomous UAVs.

Persons and Crowd Monitoring

For crowd monitoring, various research projects were proposed over the past few years, such as in [241] where the authors describe the use of collaborative micro–drones for people tracking in disaster situations. In [233] the authors present a novel airborne based high-performance crowd monitoring framework for estimating crowd density and motion using video data based on custom object detection techniques. Another application that has gained the interest of the scientific community is finding innovative means of collecting data of pedestrian traffic as it has been demonstrated to be complex and labour-intensive [288]. The authors argue that using conventional techniques, such as manual observers and on-site video records or the use of survey questions and qualitative questionnaires to investigate pedestrian flow characteristics and behaviour may be restrictive. To this end, the recent years have witnessed an increase in novel methods incorporating the use of UAVs. In [288], the authors present a feasibility analysis of UAV technology in persons and crowd monitoring and show that UAVs can be an alternative viable technology in monitoring pedestrian traffic characteristics in outdoor pedestrian zones. More recent studies propose novel large scale crowd monitoring systems [139] that take into consideration the privacy and security challenges of using UAVs for crowd monitoring [312].

Environmental Monitoring

Over the past two decades researchers have investigated innovative uses of mobile robotics in various monitoring applications. In [54] the authors explore emerging research trends for achieving large-scale environmental monitoring, including cooperative robotic teams and wireless sensor network interaction. The authors emphasise that these trends offer efficient and precise measurement of environmental processes at ultra-large scales in turn furthering the frontiers of natural sciences. In a more recent study [9], the authors stress on the constant need for monitoring the environmental features changes. The paper proposes guidelines for the design of a lightweight and low–cost UAV platform for environmental monitoring. As environmental monitoring plays a central role in diagnosing climate and managing impacts on natural and agricultural systems [190]; the research community continuously develops new systems and proposes new projects to address such needs. In [320] the authors propose AQNet, a aerial–ground wireless sensor network (WSN) system, for fine–grained air quality monitoring and forecasting in urban three–dimensional areas. The proposed system compromises of hundreds of programmable on-ground sensors working in tandem with UAVs to monitor air quality at various heights. The paper proves the scalability of the system through demonstrated experiments. This is further complemented by a comparable proposal in [236].

Agriculture Monitoring

Another emerging field with great potential for UAVs usage is agriculture. For instance [311] provides an improved remote sensing system based on an autonomous UAV. Equipped with a multi-spectral cameras, the authors demonstrate that their UAV-based system was capable of monitoring turf grass glyphosate. In turn indicating the flexibility and reliably of UAVs in precision agriculture (PA). This is further supported in the comprehensive survey in [329]. The latter emphasises that images taken by low altitude remote sensing UAV platforms have potential given their low cost of operation in environmental monitoring, high spatial and temporal resolution, and their high flexibility in image acquisition programming. The survey further outlines recent studies in the application of UAV imagery for PA. Indicating that, to provide a reliable end product to farmers, advances in platform design, production, standardisation of image geo-referencing and mosaicing, and information extraction workflow are required. This is further supported in the recent review [149]. The paper focuses on current and potential applications of thermal remote sensing in PA as well as some concerns relating to its application such as spatial and temporal resolution, atmospheric conditions, and crop growth stages. Supporting it, is [165], where the authors discuss how UAVs play a great role in transforming the farming sector. This in turn has led to a rise in a new domain known as *precision farming* that is quickly gaining attention of the scientific communities, one recent example is in [31] where the authors propose a narrow–band IoT UAV–aided networks to study various soil parameters previously not feasible to investigate.

Security and Surveillance

Taking off from military to now more commercial and public sectors, UAV security and surveillance applications have recently emerged to be a predominant domain falling under Stage 2 in Figure 3.7. From target following and tracking [313] to border control [158, 301], the scientific community is continuously working on utilising the mobility and agility of UAV platforms for security applications. In [244] the authors present a resource-usage management scheme called adaptive multi-scale optimisation (AMO) for UAV surveillance operations. The paper demonstrate AMO's benefits and trade-offs through a series of simulator runs, covering multiple use cases. Moreover, the authors in [152] discuss their designed frameworks for UAV surveillance and security systems for smart cities and marine applications emphasising on the potential such applications would have on the benefit of the society. In [85] the authors propose a new cooperative network platform and system architecture of multi-UAV surveillance. First the paper elaborates on the design concepts of a multi-UAV cooperative resource scheduling and task assignment scheme. It then explains the moving small target recognition technique as well as the localisation and tracking model using the fusion of multiple data sources. In addition, this article discusses the establishment of suitable algorithms based on machine learning due to the complexity of the monitoring area. The authors support their work by conducting real world detection and tracking experiments of multiple moving targets using the proposed multi-UAV systems. A complementary recent study [263] presents a novel surveillance optimisation and a distributed navigation algorithm for UAV network in applications of ground vehicle tracking.

Infrastructure Inspection

One additional domain that gained a lot of attention from both the research and commercial communities is infrastructure inspection. The use of UAVs offers the flexibility of reaching to places and taking measurements that were considered near impossible for their hazardous nature to human labour. The work presented in [170] provides a comprehensive review on robotic infrastructure inspection systems. The paper aggregates these studies in an effort to distil the state of the art in inspection robotics, as well as to assess outstanding challenges in the field and possibilities for the future. [262] gives a possible solution to the overcome the infrastructure inspection challenges in Japan using UAVs. The authors develop a light weight manipulator on UAV system for ageing infrastructure inspection where people cannot. Another recent paper [25] describes a mission definition system and implementation for automated infrastructure inspection using airborne sensors. The paper's main aim is improving planning efficiency with respect to state-of-the-art way point-based techniques. The obtained results for a set of representative infrastructure inspection flights, show accuracy of flight prediction tools in actual operations using automated flight control.

Search and Rescue

Search and Rescue (SAR) includes operations led by emergency services, to locate and identify assets in distress in remote or difficult to access areas. Since the early 20th century global organisations have put efforts in establishing international Search and Rescue (SAR) plans to ensure the coordination of missions. As technology developed over time, researchers have found new tools and methods to optimise SAR missions. This in turn led to exploring the potential of integrating UAVs in such SAR networks. In [292] the authors introduce small UAV systems to provide essential support to on–ground task forces in situation assessment and surveillance. As external infrastructure for navigation and communication is usually not available, such UAV systems should be able to operate with some degree of autonomy in turn classifying such applications between Stages 2 and 4 in Figure 3.7. This is further supported in [16] where the authors present an integrated data combination and data management architecture that is able to accommodate near realtime data gathered by a fleet of UAVs. The paper validates the system by illustrating two experiments. First, in the controlled environment of a military testing base, a fleet of UAVs was deployed in an earthquakeresponse scenario. Second, on an actual mission to aid with the relief operations after major flooding in Bosnia in 2014. After the success of multiple similar scenarios, research such as in [260] and [223] explore the use of complete autonomous UAV systems for SAR missions.

Logistics and On-demand Delivery

One of the segments, and key market sectors, where UAVs are increasingly becoming popular is logistics. Logistics can be defined as the management of the flow of things between their point of origin to their point of consumption in order to meet predefined requirements. They are a very cost effective solution for warehousing, container terminals and many others.

December 1st 2013 marked the beginning of a new era of commercial package delivery when Amazon announced plans for Prime Air [24]. In early 2014 the work presented in [42] discussed the potential of package deliveries using small UAVs after Amazon's promotional video exceeded 14 million views. However, at the time, not many studies have implemented practical applications in this area since several challenges needed to be addressed first. The authors in [203] highlight the potential and challenges for UAV-enabled Intelligent Transportation Systems for next-generation smart cities. With more researchers investigating the topic, [231] and the NASA technical report [324] present a good example of such work. Here the authors discuss different approaches to the typical notional small package delivery drone concepts giving an indication where future research trends are. While the origins of use cases have been first researched in military logistics applications [201] with the current global crisis we witness a shift to more commercial and more specifically efficiency critical medical deliveries [108].

Emergency and Medical Services

Another application group that has recently emerged and is continuously attracting more researchers is UAV for e-Health. One example is [133] which discusses the potential UAVs have in this segment. Furthermore, [160] examines the use of drones in Swiss hospitals. The work shows in which areas of Swiss hospitals drones can be implemented to create cost saving as well as process optimisation possibilities in order to manage increasing cost pressure and technological progress.This is further supported in [196] and [153] where the authors discuss drone-aided delivery and pickup planning of medication and test kits for patients with chronic diseases who are required to visit clinics for routine health examinations and refill medicine in rural areas. Another recent work presented in [193] where the authors stress on the time-critical optimisation of such emergency service. This is further supported in [40] where the authors present a design process of unmanned vertical take-off and landing aircraft, developed by the High Flyers team from Silesian University of Technology, who decided to participate in the Medical Express UAV Challenge competition. During the past year marked by the global pandemic of COVID-19 numerous applications within the e-Health domain have been introduced in addition to governmental initiatives like EU AiRMOUR [61].

Other Emerging Hybrid Applications

As analytical and computational capabilities of UAVs improve combined with the rapid development in sensory and actuation as well as communication and other IoT technologies, we witness a shift to Stage 4 for the aforementioned UAV applications. Relying on a higher degree of autonomy and the ability to perceive & act UAVs can be used to in varied domains. Some potential future examples include pest detection and control within agriculture, UAVs for pick up and drop off as an extension to logistics and on-demand delivery, autonomous UAV safeguards such as malicious–UAV detection and escort presented in [27, 282] and cargo as well as people pick up and drop off [315]. Within this context, researchers explore key enablers to such applications ranging from mobility and swarming behaviours for complicated tasks requiring multi-UAV operations [52] and automating the design of autonomous UAV swarms as a disruptive approach to tackle the problem of designing swarming behaviours to novel automated algorithm selection approaches [53].

To this end, the preceding subsections attempted to compile some predominant conceptual application domains under the main three devised categories of *perceive*, *act* and *perceive & act*, illustrated in Figure 3.7. Additionally, for each of the predominant application domains some empirical use–cases were highlighted from scientific literature. This is summarised in Table 3.1 below.

3.4.3 Inherent Challenges of UAVs in IoT

The value and benefits that UAVs can bring to our everyday lives and to our future cities is undeniable, however, being part of the next generation IoT, UAVs face the inherent vulnerabilities and threats of other smart IoT devices. The unprecedented connectivity combined with foreseeable large number of data being exchanged by

UAV Application Taxonomy

Category	Application domain	References
Perceive *Stages 1-2*	**Telecommunications** *Examples:* *-Temporary & emergency networks* *-Hybrid aerialterrestrial infrastructure*	[57, 58, 70, 86, 111, 142, 146, 182, 194, 210, 211, 214, 235, 269, 304, 331]
	Asset and Traffic Monitoring *Examples:* *-Monitoring car traffic patterns* *-Monitoring traffic densities*	[50, 107, 143, 147, 205, 221, 222, 270]
	Persons and Crowd Monitoring *Examples:* *-Monitoring safety of staff & personnel* *-Monitoring pedestrian traffic*	[139, 233, 241, 288, 312]
	Environmental Monitoring *Examples:* *-Air quality &climate diagnosing* *-Mapping & land surveying* *-Wildlife monitoring*	[9, 54, 190, 236, 320]
	Agricultural Monitoring *Examples:* *-Multi-spectral imagery and crop monitoring* *-Precision farming* *- Mapping pesticides*	[31, 149, 165, 311, 329]
	Security and Surveillance *Examples:* *-Moving target detection & tracking* *-Security boarder control* *-Parameter surveillance*	[85, 152, 158, 244, 263, 301, 313]
	Infrastructure Inspection *Examples:* *-Hazard identification & detection* *-Automated infrastructure inspection*	[25, 170, 262]
	Search and Rescue *Examples:* *-Relief operations* *-Search & identify disaster victims*	[16, 223, 260, 292]
Act *Stage 3*	**Logistics and On-demand Delivery** *Examples:* *-Last-mile delivery* *-Logistics & cargo transport*	[24, 42, 108, 201, 203, 231, 324]
	Emergency and Medical Services *Examples:* *-Blood sample & medicine transport* *-Emergency response in remote locations*	[40, 61, 133, 153, 160, 193, 196]
Perceive & Act *Stage 4*	**Other Autonomous Applications** *Examples:* *-Warehousing & product sorting* *-Pest detection & spraying* *-Search, detect & extract* *-Autonomous UAV safeguards*	[27, 52, 53, 282, 315]

TABLE 3.1: A summary of UAV application domains and corresponding illustrative use–case examples based on the devised categorisation.

IoT–enabled UAVs operating in the low–altitude airspace present a set of security and data related challenges [255] let alone the physical and operational safety risks.

Security, Data Protection and Privacy Challenges

As UAVs become more connected they naturally inherit from the security privacy and data protection challenges in IoT. Over the recent years, these challenges have been continuously addressed in scientific literature [5, 122, 202, 256, 332]. The authors in [256] present a summary of some of the main UAV privacy and security threats, illustrated in Figure 3.8. Based in the work in [256] the figure presents the devised taxonomy of security threats, categorised under *confidentiality*, *integrity* and *availability* threats.

Besides the security challenges that obstruct the full realisation of connected UAVs, are the inherited data protection and privacy related threats of being mobile IoT–connected devices and platforms. Most UAVs' commercial applications and specifically those in cities, require a lot of sensory as well as location and other critical data to be collected and transmitted over the internet hence posing a set of threats in addition to direct violations to General Data Protection Regulation (GDPR) [257] such as lack of transparency, data quality, profiling and data security. Nevertheless, UAVs extreme mobility and modes of operation pose additional physical threats to both people and property within cities.

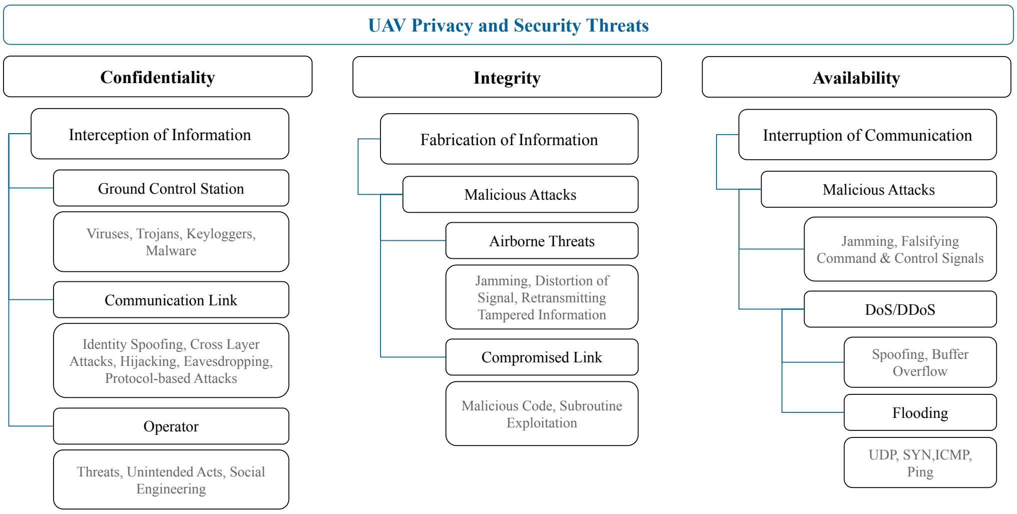


FIGURE 3.8: Taxonomy of UAV privacy and security threats based on [256]

Operational Management Challenges

The majority of UAV applications in literature require the operation of single as well as swarms of UAVs in the low–altitude airspace [252]. This in turn introduces a new set of challenges in safely let alone efficiently managing the operation of such agile, mobile aerial vehicles over populated cities. Moreover, the lack of consensus on airspace structure, not to mention the lack of technical standards and minimum requirements for things like collision avoidance, remote identification as well as the non-existent unified data model for communication add further complexity to an already convoluted problem.

One initial step towards tackling these challenges is understanding the associated risks and establishing some tools to aid in their modelling. The authors in [197] introduce a set of risks that need to be quantified or qualified and mitigated. Similarly, in [106] a comprehensive risk assessment model based on collision probability is proposed for UAV operation in urban environments. Three risk categories are considered, namely property, people and vehicles. As the topic of UAV risk assessment continues to gain more attention in the scientific community, more novel approaches are proposed that take further external arguments into consideration such as flight conditions [105, 239, 240]. However, one limitation in most approaches is that they do not consider the operational status of the various internal UAV subsystems for example, time to maintenance or battery level when conducting flight-related risk assessments. While from a macroscopic perspective simplifying UAVs to mass points within a flight environment can arguably suffice, UAV operational risk assessment should be more comprehensive as UAVs are a complex system consisting of multiple subsystems operating in tandem, each with their own fault tolerances and accuracy levels. In [283], for instance, the authors develop a novel data-driven fuzzy comprehensive evaluation approach to monitor the condition of the various UAV subsystems and incorporate them into the risk assessment model.

3.5 UAV Technical Standardisation

Technical standardisation is the process of implementing and developing technical standards based on the consensus of different parties that include industry, users, interest groups, governments and other stakeholders. The main aim of technical standardisation is to help maximise interoperability, safety and quality as well as facilitate commoditisation of processes. The idea of standardisation is comparable to the solution for a coordination problem, a situation in which all parties can only realise mutual gains by making mutually consistent decisions.

UAV and UTM technical standardisation lies in the conjunction of the well–established aviation industry and the evolving Information Communication Technologies (ICT) standardisation. However, in contrast to IoT technical standardisation as one of the pillars of ICT, UAV standardisation is relatively recent with only a few published standards.
Nevertheless, while the majority of the working groups and committees were only initiated in the past few years, the technical committees efforts are picking up pace, benefiting from the well-established aviation standards, to correspond to the growing market needs.

On the regulatory side, the recent rapid growth in the commercial UAV market has encouraged authorities, regulators to collaborate with SDOs to form working groups and collaboratively address some of the pressing issues, some notable examples of regional SDOs include the European Organisation for Civil Aviation Equipment's (EUROCAE) working group (WG 73), the European Union Aviation Safety Agency (EASA) and EUROCONTROL Joint as well as international SDOs including International Civil Aviation Organisation (ICAO) [298], ISO TC20/SC16 [**iso**]on Unmanned Aircraft Systems and IEEE-SA P1939.1 for Structuring Low Altitude Airspace for UAV Operation [114]. In response to the market, SDOs aim to reach consensus over guidelines and standards to safeguard the UAV economy and despite their geographical scope - local, regional or international - they all follow similar themes as explored below (c.f. Figure 3.9) from the more defined to the most recent, indicating that UTM technical standards build on all other sub-domains.

This section gives an overview of UAV and UTM technical standardisation as well as the current efforts and developments within the relevant committees.

Classification and Terminology

Being the well–developed theme of UAV standardisation, standards under this theme are mainly focused around defining terms relating to UAVs that are widely used in science and technology. Additionally, they aim to specify requirements for the classification and grading of civil unmanned aerial vehicles with a wide enough scope to include heavier than air aircraft as well as lighter than air aircraft of any possible

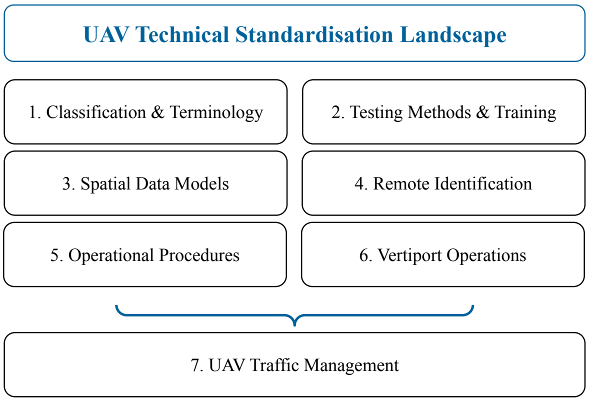


FIGURE 3.9: Summary of UAV technical standardisation activity domains from the more defined to the most recent, indicating that UTM standards build on all other sub-domains.

architecture.

Such documents apply to the industrial conception, development, design, production and delivery of civil UAVs as well as their modification, repair and maintenance. Current efforts are to consider risk-based classification or categorisation of UAV operations within their scope mainly because risk-based classification could be prerogative of aviation authorities.

Testing Methods and Training

As for any new technology, quality plays a significant role in public acceptance. Standardisation committees therefore work alongside industry and governments to define various testing methods to ensure all manufacturers and operators use comparable benchmarks. Moreover, most of standards under this scope devise the minimum requirements for various systems and subsystems with UAVs. While having benchmarks and testing methods is a good initial step, it is far from enough without the accompanying training guidelines for personnel as UAVs are expected to operate within populated cities in the near future and hence, safety is paramount.

Spatial Data Models

While the majority of allowed UAV flights are within the Visual Line of Sight (VLOS), the greater commercial benefit comes from applications that would inevitably require authorisation Beyond Visual Line of Sight (BVLoS). In order to facilitate such transition, standardisation organisations work on defining data structure and models to represent UAVs spatial environment. Such data models include static and dynamic obstacle representation in addition to other elements of the airspace.

Remote Identification

Identification systems for vehicles, let alone unmanned aerial vehicles, is essential for their safe operation and management. Hence, remote identification is a foundational component of integrating UAVs into the low altitude airspace of cities. With various companies in the market proposing different means of identifying UAVs remotely, SDOs are faced with the challenge of reaching consensus on a unified standardised means of identification.

Operational Procedures

The standards that follow this theme - mainly international standards, aim to specify the requirements for safe commercial UAV operations within the low–altitude airspace. Such standards and guidelines include procedures of operation for various UAV scenarios including people-carrying.

Vertiport Operations

In contrast to manned aviation where airports are stationary and well-defined, to UAVs and specifically multi-rotor UAVs, every place is a potential airport. In line with this, SDOs are currently working on defining operational standards for UAV vertiports as vertical landing and take-off sites for UAVs.

UAV Traffic Management

Finally, building on all the above standards as well as the established aviation and communication standards, UTM–dedicated working groups are the latest addition to most SDOs. UAV traffic management is crucial to ensure compliance and safe operation within the airspace by standardising foundational functions including registration, remote identification, UAV tracking in addition to communication systems and data models as well as geo-limitation and operational procedures. Some notable examples of technical committees include ISO TC20/SC16 WG4 on Unmanned Aerial Systems Traffic Management [130].

3.6 Summary of Prospects and Challenges

The rapid adoption of Internet of Things (IoT) has encouraged the integration of new connected devices such as Unmanned Aerial Vehicles (UAVs) to the ubiquitous network. UAVs promise a pragmatic solution to the limitations of existing terrestrial IoT infrastructure as well as bring new means of delivering IoT services through a wide range of applications.

The value and benefits that UAVs can bring to our everyday lives and to our future cities is undeniable, however, being part of the next generation internet of things, UAVs face the inherent vulnerabilities and threats of other smart IoT devices in security, data protection and privacy. Moreover, the lack of technical standards and minimum requirements for things like collision avoidance, remote identification as well as the lack of a unified data model for communication as well as to represent UAVs and their environment add further complexity.

Simply put, in order to fully realise the potential of UAVs, industry and standardisation committees as well as research communities should work on developing new methods and systems to help safely manage and operate UAVs. One potential solution that is further discussed though-out this work is a dedicated UAV Traffic Management (UTM) system [264], an infrastructure building upon IoT concepts, such as its layered design, to complement conventional Air Traffic Management (ATM) by facilitating data exchange between UAVs as well as different stakeholders.

End of Chapter 3

Part II

Unmanned Aerial Vehicles Traffic Management System (UTM)

Chapter 4

UTM State of the Art

4.1 Introduction

The significance and importance of Unmanned Aerial Vehicles (UAVs) is growing exponentially. As smart devices and platforms, UAVs range from small off-the-shelf recreational UAVs, commonly referred to as drones to large aircrafts potentially capable of transporting cargo and people. Previously, chapter 3 outlined and discussed possible applications and use-cases for UAVs ranging from goods infrastructure monitoring to on-demand delivery and search & rescue. However, the airspace integration of such novel systems is still a major challenge. Up until this day, there is no concrete regulatory framework or established traffic management infrastructure to enable and securely manage the widespread use of general airspace for UAVs.

The main goal of this chapter is therefore to provide an introduction and overview of UAV Traffic Management systems UTM. The structure is, hence, as follows, Section 4.2 presents a conceptual overview of UTM constructs and airspace management followed by the key functionalities in Section 4.3. Section 4.4 explores state of the art. Finally Section 4.5 concludes the chapter by highlighting the key research questions and directions explored in the remaining chapters of this manuscript.

4.2 Inception of UTM Construct

The inception of UAV traffic management systems in the recent years is a result of the need of having a clear framework at national, regional and international levels to guide the rapidly evolving UAV technologies and to enable as well as catalyse the

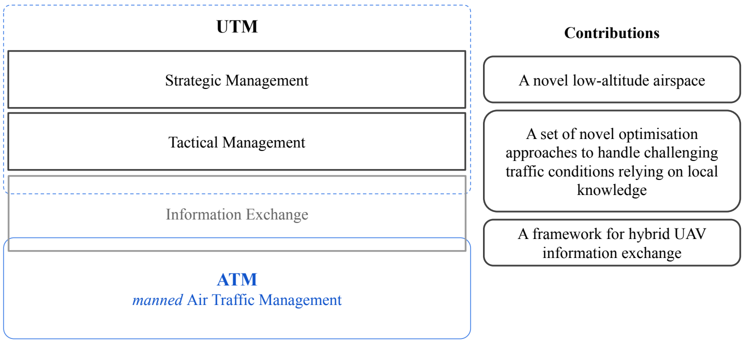


FIGURE 4.1: Illustration of UTM's role in strategically and tactically managing the airspace, UAV traffic as well as facilitating data exchange between stakeholders.

creation of a market for UAV services. UTMs will facilitate the growth of this new promising sector of the economy, on one hand, while ensuring public safety on the other.

However, since its conception [3, 10] the definition of the term UTM remains fuzzy. While most acknowledge that a UTM is a specific aspect of air traffic management responsible for the operational safety of UAVs as defined by ICAO [298], many fail to see that similar to IoT, a UTM is a system of systems that functions by facilitating collaborative integration of people, information, technology as well as services by incorporating heterogeneous air, ground and space-based communication technologies and standards. It can be therefore deduced that the main goal of a UTM system is to facilitate data and information exchange between stakeholders as well as manage and monitor UAVs with diverse characteristics safely, together while ensuring safe integration with other airspace users including helicopters, gliders, and paragliders for a future fully-integrated manned and unmanned airspace. It becomes apparent that a UTM is a multi-stakeholder system of systems where every actor group has different needs and incentives. On one hand industry service providers and operators want to simplify bureaucratic procedures and have the ability to fully utilise the potential of UAVs to bring value-added services, and on the other authorities, administrators and regulators want to ensure safe operation and compliance. This in turn emphasises the level of complexity of a UTM system.

The expected complexity of a successful traffic management system can be abstracted to spatial and time-related interactions between aircrafts, whether manned or unmanned, operating in a given airspace during a defined period of time. Consequently, such presumably high complexity may be reduced at both the strategic and tactical levels.

Simply put, the goal of a UTM system (c.f. Figure 4.1) is therefore to strategically and tactically manage the airspace, UAV traffic and facilitate data and information exchange between stakeholders as well ensuring safe integration with other airspace users including helicopters, gliders, and para-gliders for a future fully-integrated manned and unmanned airspace.

To this end, the following subsections explore both stages and their correlation to the UTM functions or services.

4.2.1 Strategic Airspace Management

The UAV traffic management system is accountable for managing the airspace and traffic movements on a strategic and tactical level.
At the strategic level, the UTM system is responsible for efficiently planning and segmenting the available low-altitude airspace with the main goal of making optimal use of the shared resource. Such efficient airspace management builds on a suitable airspace structure [252] to avoid of permanent segregation between different users of the airspace [74]. This proactive approach can be achieved by dynamic allocation of airspace taking into consideration performance and flight requirements to efficiently utilise airspace and optimise the planned traffic in order to ensure safe UAV operations even in dense traffic scenarios.

4.2.2 Tactical Airspace Management

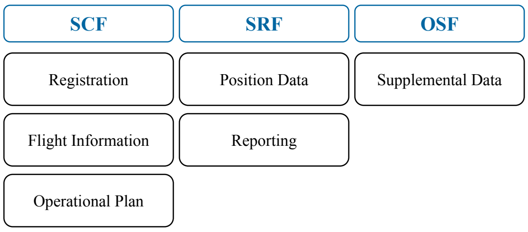
Subsequently, complementing the proactive strategic stage of airspace management is the dynamic tactical stage. The main aim of this stage is to maintain separation and mitigate collision risks therefore a reliable underlying information management systems is crucial. This underlying information management system collects traffic data including 3D positions, heading and velocities in order to provide situational awareness and to be able to issue traffic alerts or geo-limitation warnings to airspace users when needed - further explored in Chapter 6.

4.3 Key Functions of a UTM

To this end, the term UTM in scientific literature is used as an overarching umbrella term to represent the infrastructure encompassing all systems that assist UAVs to depart from a vertiport or aerodrome, transit airspace, and land at a destination aerodrome or vertiport, safely, including traffic services, airspace density and traffic flow management, integration with manned aviation, authorities as well as others by facilitating data exchange between the different stakeholders as explained above. In this subsection we highlight the key functions of a successful UTM system as compiled from industry proposals, scientific literature and standardisation organisations. The devised proposal categorises UTM functions as either *safety critical (SCF)*, *safety related (SRF)* or *operational support (OSF)* where,

- *SCF* are those that if lost or degraded as a subsequent to any incorrect would result in total service disruption and collateral damages;
- *SRF* on the other hand are functions that have the potential to contribute to the violation of or achievement of a safety goal, but whose loss or degradation would not on its own be sufficient to cause catastrophic consequences;
- finally, *OSF* include any web-based tools and information provided by service providers to UAV operators with the aim of supporting safe and efficient planning and execution of a UAV mission.

With this broad categorisation in mind, the key UTM functions can then be further classified based on compiled definitions and functional descriptions of ICAO's Core Principles for Global Harmonisation [298], Concept of Operation for EuRopean UTM Systems (CORUS) [18] and Federal Aviation Authority (FAA) Concept of Operations [**jiang2016unmanned**], into the following five main function classes shown in Figure 4.2 and are further explored below in subsections 4.3.1-4.3.6 based on our work in [166].



SCF	SRF	OSF
Registration	Position Data	Supplemental Data
Flight Information	Reporting	
Operational Plan		

FIGURE 4.2: Classification of UTM main functions as *safety critical (SCF)*, *safety related (SRF)* or *operational support (OSF)*.

4.3.1 Registration Function

The registration function provides a mechanism to register as well as share authorities' certified UAV records in order to ensure a safe operation within the airspace. The registration functions are therefore classified as pre-flight Security Critical Functions (SCF) and information provided through this function should be managed by the national authority or other appropriate third entity and regulated in each country according to their specifications of airspace laws and regulations. The registration function hence, encompasses - however not limited to - the following:

- Remote Pilot Registration – register and manage information about certification/classification and skill of remote pilot. The information managed by this function could be provided appropriate third entity, such as national authority and police. The information to be registered and managed, and the provision destination are regulated in each country according to the specifications of various international standards and based on laws and regulations.

- UAV Registration – register and manage information about UAVs such as type of aircraft, performance, specifications, aircraft number, owner, on-board equipment, etc. The information managed by this function could be provided appropriate third entity, such as national authority and police. The information to be registered and managed, and the provision destination are regulated in each country according to the specifications of various international standards and based on laws and regulations.

- Operator Registration – register and manage information about operator who utilise UAV on their business. Such as name of operator, authorisation information, etc. The information managed by this function could be provided appropriate third entity, such as national authority and police. The information to be registered and managed, and the provision destination are regulated in each country according to the specifications of various international standards and based on laws and regulations.

4.3.2 Flight Information Management Function

The flight information management function is a SCF and aims to ensure the safe operation of UAVs as well as manned aircrafts operating within the same airspace. Such function is responsible for handling the exchange of traffic and aeronautical information with air traffic management systems within the shared airspace. The flight information management function hence, encompasses - however not limited to - the following:

- Aeronautical Information Management – facilitate aeronautical information exchange which is necessary for safe UAV operation.
- Collaborative Interface with Air Traffic Control (ATC) – provide UAV operators with communication means to contact ATM services when they fly or enter into controlled airspace.
- Airspace Organisation and Management – design the structure of airspace and manage the usage thereof to achieve safe and efficient UAV operations.
    - Airspace Organisation – define where UAV activity should be prohibited or restricted within the airspace and to define the routes where UAVs can fly safely.
    - Geo-awareness – publish airspace definition information defined by airspace organisation function.
    - Airspace Access Control – control UAVs access to predefined airspace and to monitor and permit UAVs to enter or exit a controlled airspace according to characteristic of mission and the UAVs' performance.
- Demand and Capacity Management – set proper capacity on each airspace and to monitor traffic demand of UAVs where the capacity values are determined by established analytical statistical estimation methods. In situations where the demand is expected to exceed capacity, the UTM coordinates operation plan with each operator to form a safe and efficient traffic flow.
- Traffic Information Exchange – exchange UAV and manned aviation information with ATM.
- Flight Plan Exchange – exchange UAVs' operation plan and manned aircrafts' flight plans between UTM and ATM.

4.3.3 Operation Plan Management Function

The operation plan management function is a SCF which aims to aid in the flight route plan authorisation to ensure UAV operations are carried out safely and efficiently. The function also supports necessary plan changes when flight conditions such as weather change during operation.

- Operation Planning – support operators to select safe efficient flight routes taking into considerations constraints on the flight path such as geo-limitations, interference with terrain, severe weather conditions and the capabilities of the UAVs and remote pilots.
- Strategic Conflict Management – help ensure and maintain separation between UAVs as well as between UAVs and manned aviation.
- Operation Plan Approval – confirm completeness and acceptability of the operation plan filed and return the result to the operator. The function additionally confirms that the operation plan does not interfere with other UAVs or restricted areas of the the airspace and provide the operator with the final approval.

- Operation plan sharing – share UAVs' operation plans among UTM actors.

4.3.4 Position Data Management Function

The position management function is a SRF that aims to manage the position-related information provided by the UAV to confirm that the operation is executed correctly as per authorised plans.

- UAV Tracking – grasp and track the location information of individual UAVs, including position, altitude, speed, etc. based on the information obtained in their identification.
- Tactical Conflict Management – provide information for securing consistency with the operation plan, proper distance between UAVs and between UAVs and manned aircrafts based on the UAVs' tracking data. This function is used in conformance monitoring.
- conformance Monitoring – monitor the operation status of the UAV and monitor inconsistency with operation plans like route of flight, altitude, proximity to non-fly zone, terrestrial structures and other UAVs, remaining fuel level to notify the operator of any abnormal status of UAVs.
- Conflict Advisory and Alert – provide information for securing consistency with the flight plan, proper distance between UAVs and between UAVs and manned aircrafts based on tracking data.
- UAV Identification – provide individually assigned referral ID to UAVs and remote pilots. Such ID includes detailed information of the UAV including model, model type, manufacturer, performance, owner, and operator.
- Flight Data Recording – record the data reported by Position Report and Conformance Monitoring.
- Flight Log – record and manage flight time of UAV and remote pilot.

4.3.5 Reporting Function

As a SRF, the reporting function collects and shares the incident or accident report on UAV operation from operators or third parties for analysis in order to prevent recurrence.

- Incident and Accident Reporting Provision – provide reports from operators and registered UTM actors when an incident or an accident occurs.
- Citizen Reporting Provision – provide reports from third party persons when an incident or illegal operation is observed.

4.3.6 Supplemental Data Supply Function

As the name suggests, the supplemental data supply function is an OSF that provides UTM actors with supplemental data, such as weather information as well as maps or other supplementary data to enable efficient operation. Some of these include the following provisions:

- Geospatial Information Provision – provide UTM actors with geographic information, including terrain, buildings and obstacles, for safe operation.
- Navigation Coverage Provision – provide UTM actors with operating status and coverage area of navigation assistance equipment.
- Population Density Information Provision – provide UTM actors with information on population density to estimate the risk by which the operation affects to the ground.
- Weather Information Provision – provide UTM actors with Meteorological information to plan and conduct safe and efficient operation.
- Communication Coverage Information Provision – provide UTM actors with operating status, coverage area and signal strength of air-to-ground communication means.

4.4 UTM Concept of Operation

The role of UTM is paramount when multiple UAVs operate within the confinement of a shared airspace. In order to ensure safe and efficient operations within the limited shared resource, UTM has to offer a wide range of services and functions as discussed in Section refsec:UTMfunc ranging from vehicle identification, conflict detection & resolution, localisation & tracking to scheduling and other supporting functions. The envisioned UTM infrastructure should additionally allow seamless integration of heterogeneous systems and facilitate data exchange between various stakeholders. Supported by the foundations being laid down by Standard Development Organisations (SDOs) recently established working groups [254], research institutes and companies have recently proposed multiple UTM projects spearheaded by NASA Ames Research Center in close collaboration with FAA and over 125 industry partners [10, 155]. The initial proposal for UTM systems by NASA [10] was created as an information management system followed by the U-Space project by the European Commission lead by the European Aviation Safety Agency (EASA) [3, 112] with the more ambitious aim of integrating manned and unmanned aviation in a single safe sky. While both the NASA-FAA and EU U-Space concepts are accepted by most of Civil Aviation Authorities and general aviation stakeholders. The authors in [249] argue that it still remains unclear whether these concepts of operation would be standardised and globalised or would remain confined by local and regional regulations. The work in [249] further explored the UAV research trends and emphasises that even though, the scientific research metrics such as number of publications per year, focused on UAVs is exponentially growing year over year for the past decade, most focus on specific UAV challenges and only recently researchers started addressing the challenges directly related to UTM holistically as explained below.

The past few years and have shown a growth in interest in UTM and UTM–related topics from the research communities which is evident through the increased number of publications as explained in [249]. While initially, the models and approaches presented in scientific literature only focused on specific domains, the recent years have witnessed an increase in publications following more holistic approaches that account for the benefits and challenges experienced by the different UTM stakeholders. According to [249], one of the first proposals for a UTM construct - *"Internet of*

Drones" [94] - emphasised the importance of such interdisciplinary approaches by combining best practices and techniques in ATC networks, cellular communication as well as internet protocols to devising one of the first UTM constructs in scientific literature. Since then we have witnessed a clear interest in such holistic research as seen in [8, 36, 45, 67, 179, 181, 197, 249, 253, 259, 319] on UTM systems, in addition to domain-specific research on airspace design in [7, 102, 103, 135, 161, 192, 232, 238, 252, 286], collision avoidance and risk mitigation in [35, 91, 92, 101, 105, 106, 157, 228, 229, 239, 240, 268, 325, 334] and communication and cybersecurity in [5, 6, 71, 80, 122, 134, 141, 151, 174, 178, 188, 189, 199, 202, 230, 256, 326, 332] as summarised below in Table 4.1.

UAV Traffic Management Development

Area of Contribution	**References**
Airspace Structure & Design	[7, 102, 103, 135, 161, 192, 232, 238, 252, 253, 286]
Communication & Cybersecurity	[5, 6, 71, 80, 122, 134, 141, 151, 174, 178, 188, 189, 199, 202, 230, 256, 326, 332]
Collision & Risk Mitigation	[35, 91, 92, 101, 105, 106, 157, 228, 229, 239, 240, 268, 325, 334]
Development of UTM Systems	[8, 36, 45, 67, 179, 181, 197, 249, 253, 259, 319]

TABLE 4.1: Non-exhaustive list of recent contributions from the UTM perspective.

4.4.1 NASA UTM Concept of Operation

NASA's conceptual framework for a UTM, one of the earlier concepts, initially proposed in 2013 and later presented at a NASA–Industry workshop in 2014 [10]. In 2015, in a UTM convention organised by NASA, industry as well as UAVs operators expressed the need for having a UTM system to manage the operation of UAVs at the low–altitude airspace [10]. In response to the convention, the Federal Aviation Authority (FAA) together with NASA formed a UTM Research Transition Team (RTT) in 2016 [165] to jointly undertake the development and eventual implementation of such UTM system [156].

The scope of the concept of operation (ConOps) of NASA's UTM focuses on UAV operations below 400 feet (122 meters) above ground level (AGL) and addresses the increasingly complex UTM operations within and across both uncontrolled (Class G) and controlled airspace environments. The ConOps additionally sets out the national UTM architecture (c.f. Figure 4.3) as well as addresses scenarios where UAV operations take place BVLOS as well as within controlled airspace. The ConOps lists out a set of functions and roles of all of the UAV operators, UAV Service Suppliers (USS) as well as authorities and administrative bodies like the FAA as well as the corresponding level of responsibility of every actor. A summary adopted from [156] is presented in Table 4.2.

4.4.2 EU U-space Concept of Operation

Not much longer after the NASA UTM concept was initiated, the ConOps of European UTM known as U-space was announced. U-space is defined in according to [297] to incorporate a new set of services as well as procedures designed specifically to support the safe, efficient and secure UAV operations within the European. Additionally, U-space takes into consideration conceptual elements introduced by the

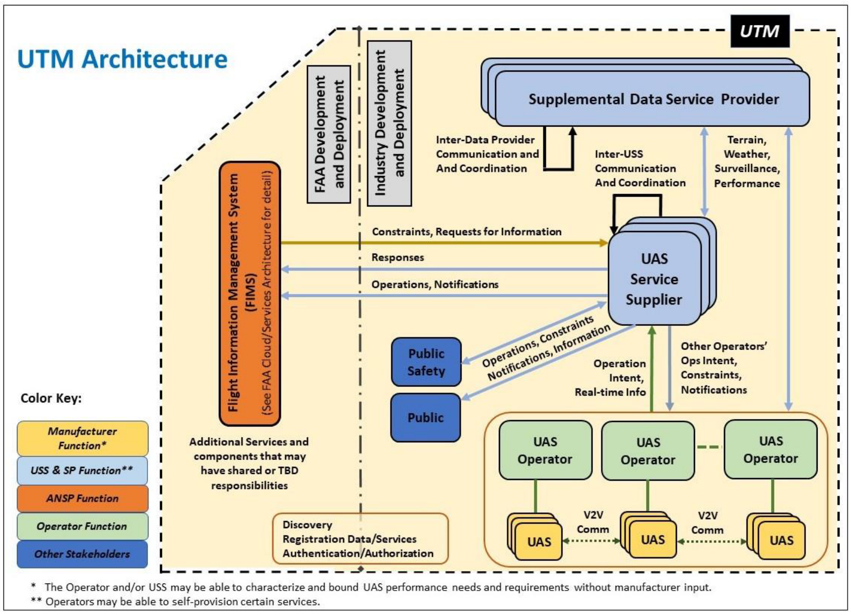


FIGURE 4.3: NASA's UTM architecture [156].

Summary of NASA UTM Functions

Function		Entities [P]rimary / [S]upport Operator	 USS	 FAA
Separation *(B/VLOS)*	UAV - UAV	P	S	
	UAV - Manned aircraft	P	S	
Hazard/Terrain Avoidance	Weather Avoidance	P	S	
	Hazard avoidance	P	S	
	Terrain avoidance	P	S	
	Obstacle avoidance	P	S	
Status	Operations status	S	P	
	Flight info archive	P	S	
	Flight info status	P	S	
Advisories	Weather info	P	S	
	Hazard info	P	S	
	Hazard alerts	P	S	
Planning, Intent & Authorising	Intent sharing	P	S	
	Intent negotiation	P	S	
	Authorisations		S	P
	Control of flight	P		
	Airspace allocation		S	P

TABLE 4.2: Summary of NASA's UTM functions and roles adopted from UTM ConOps [156].

European Unions (EU) regulations, such as EU's classification of UAV operations and their corresponding requirements.

In contrast to the 400 feet UAVs operational limit set by NASA UTM, U-space considers UAVs operations up to 700 feet (213 meters) AGL. Furthermore, U-space divides the UAVs operations according to three broad operational classification namely, *open*, *specific* and *certified*. The definitions of the different categories were proposed by the European Union Aviation Safety Agency EASA and published in the 2019 regulations in [173].

Additionally, U-Space concept of operation divides the low–altitude airspace into three different volumes as explained in [18]. The devised classification is based on the following considerations:

- The numbers of expected UAV flights;
- The ground risk when flying over populated areas;
- The air risk based on the other operators in the shared airspace;
- Security, privacy as well as other factors such as public acceptance;
- Finally, the availability of mission-required U-space services.

The devised airspace volumes are distinct in terms of support service offered, types of operations allowed as well as their access and entry requirements. The 700 feet of available airspace is made up of these three volumes signified as X, Y and Z respectively. Where in X no conflict resolution service is offered, in Y only pre-flight strategic planning support is offered, and in contrast in Z all strategic and tactical services are offered [296]. In contract to NASA UTM's 5 functions, the U-space concept of operation defines a set of 8 core functions for U-space ranging from UAV identification and tracking to the integration with manned aviation traffic management ATM. A summary of the main 8 functional categories each with the respective sub-functions is illustrated in Figure 4.4 adopted from [295].

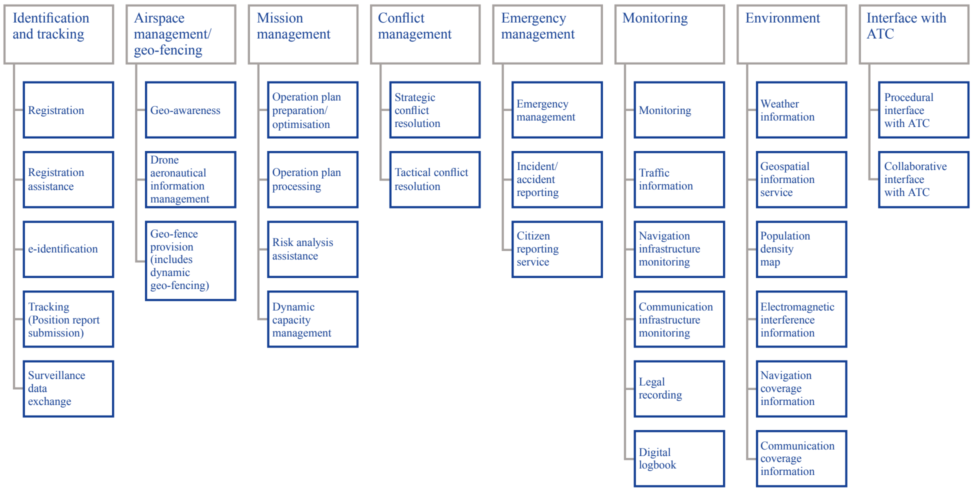


FIGURE 4.4: Summary of U-Space main 8 functional categories each with the respective sub-functions as adopted from [295].

4.4.3 UAV Traffic Management Demonstrations

Over the course of the past few years a considerable number of UTM constructs have been proposed by governments, standardisation committees and industries. This subsection highlights a few examples of these UTM systems found in literature.

Taiwanese UTM

Another example of UTM proposed as well as demonstrated is the Taiwanese UTM [179]. In [249] the authors analyse the Taiwanese UTM concept of operation and according to their work, The Taiwanese UTM relies in its core on the ability to track and monitor UAVs within the airspace. For the demonstration of the UTM - surveillance flight demo - Automatic Dependent SurveillanceBroadcast (ADS-B) was used. The UTM concept of operation proposes that it is the duty of ANSPs to alert pilots of any traffic within 600m radius. The concept of operation proposes a pre-flight process of flight scheduling and approval however, all collision avoiding decisions during flight are up to the operator [179].

Swiss U-space

Within the context of EU's UAV traffic management, the Swiss U-space concept of operation presents Switzerland's vision for incorporating UAVs within one of Europe's busiest national airspace. The Swiss U-space describes the associated high–level requirements as well as outlines the national UTM architecture [26]. The architecture of the Swiss UTM adopts a federated set of services designed with the aim of facilitating safe, secure and efficient integration of multiple UAVs within the same airspace as manned aircrafts. The concept of operations emphasises that airspace and traffic flow management in addition to various monitoring services would represent the core functions of the Swiss U-space. Additionally, its architecture aims to support multiple service providers in operational data exchange and to manage the balance of demand and airspace capacity as well as facilitate authorisation requests, and provide directives and advice to UAV operators.

Industry and Others

Additional to what is presented in [179, 181, 229, 319], literature provides other constructs and architectures as part of on-going U-space and UTM projects. Some of the most notable ones include China's Civil UAS Operation Management System (UOMS) or the Japanese UTM. Furthermore, the recent years have witnessed rise in UTM proposals from private industry including AirMap UTM and Unifly UTM as well as GuardianUTM by Altitude Angels. This is in addition to current standardised architectures being developed by Standardisation Development Organisations (SDOs) such as the on-going work at ISO TC20/SC16 on UTM development [130]. The interested reader can find an exhaustive list of commercial concept architectures and constructs in [28].

4.5 Summary

The scope of this manuscript focuses on the next generation distributed airspace traffic systems that is capable of supporting large–scale operations of heterogeneous swarms of autonomous vehicles, which is non-existent to date.

The evolving aviation industry and the introduction of UAVs as smart connected platforms built with full autonomy in mind, we can predict a decrease in demand for pilots for standard operations [100]. Further more, the rapidly expanding UAV applications make it safe to predict a near future where they would dominate the low altitude airspace over populated cities. This in turn adds to the complexity of air traffic management and emphasises the need of having a reliable UTM in place to manage their operation. While the proposed systems discussed throughout this chapter offer a viable solution, such centralised systems will not be able to cope with the highly dynamic nature of the UAV traffic networks, let alone the dynamic geo-limitation, intrusion detection and communication challenges.

The expected complexity of air traffic management can be defined as the level of either perceived or actual spatial and time-related interactions between aircrafts, whether manned or unmanned, operating in a given airspace during a given period of time. Consequently, such presumably high complexity may be reduced at both the strategic and tactical levels. At each of these levels, it can have a spatial-based nature such as airspace structural design and assignments such as airways, routes and activity zones as well as performance-based solutions such as traffic flow management. In that context, complexity can be understood as a demand characteristic of air traffic that is to be served by an appropriate management system [217]. To this extent, we envision a distributed UTM where autonomous UAVs dynamically plan their paths based on local information and decisions while optimising ad-hoc communications. This in turn would allow for better resilience and scalability of the system.

Given the hypothesis that an Unmanned Aerial Vehicle Traffic Management system (UTM) with distributed decision making allows for better scalability and resilience, the main goal the remainder of this manuscript is to investigate the falsifiability of the hypothesis by examining the possibility of developing a fully distributed UTM that is capable of intelligently handling highly dynamic and challenging traffic conditions. Over the following chapter, the manuscript aims to address the main research questions highlighted in Chapter 1.

- Chapter 5 explores the strategic airspace management aspect of UTM by investigating and assesses how the structure of the airspace can be defined and how UAVs traffic can be modelled.
- Chapter 6 builds on Chapter 5 by investigating the tactical airspace management aspect of UTM by exploring the UAV connectivity infrastructure and devising an information exchange framework.
- Chapter 7 and 8 address the core functions of UTM by exploring and evaluating traffic behaviour based on proposed path planning optimisation algorithms.

End of Chapter 4

Chapter 5

Low-Altitude Airspace Model

5.1 Introduction

The expected complexity of a successful traffic management system can be abstracted to spatial and time-related interactions between aircrafts, whether manned or unmanned, operating in a given airspace during a defined period of time. Consequently, such presumably high complexity may be reduced at both the strategic and tactical levels. At each of these levels, the solution to addressing the traffic management complexity is not limited to performance-based and traffic flow solutions on the contrary the it is rooted in the spatial-based nature of airspace structural design including assignments of airways, routes and activity zones. In that context, and as emphasised in Chapter 4, a mandatory first step towards a distributed UTM is to design and model the low-altitude airspace as its structure will have a significant role in air traffic management.

To this end, the main contribution of this chapter is addressing the strategic airspace management component of the complex problem of UAV traffic management at an abstract level by proposing a structure for the uncontrolled low-altitude airspace. The chapter is structured as follows. Section 5.2 presents an overview of the history of airspace structure as well as key terminology, standards and references that emphasise the correlation between the airspace structure and strategic traffic management. Section 5.3 explores state of the art and presents the proposed low-altitude airspace structure as a multi-weighted multilayer network, followed by application scenario and operational use-case example in Section 5.4 Finally, Section 5.5 summarises the chapter, highlights how performance-based traffic flow solutions builds on the presented spatial-based solution and emphasises the role of efficient communication and information exchange.

5.2 Airspace Structure

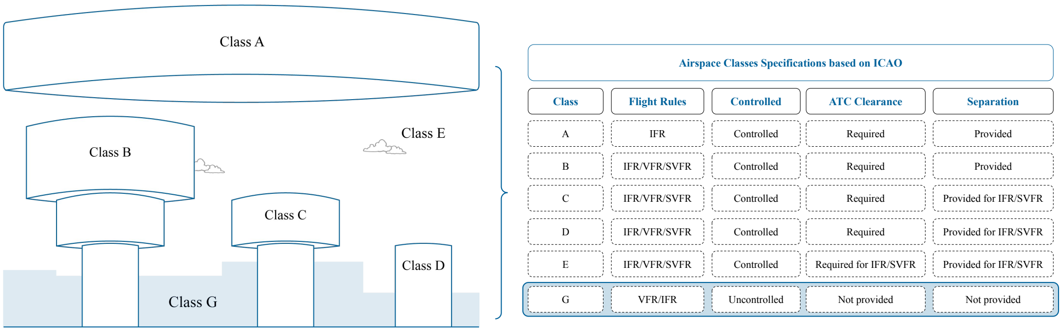
In order to design and model the low-altitude airspace to enable a distributed UAV traffic management system, this section presents the background and basic notions. To this end, the following subsections present an overview of the history of airspace structure and elaborate on the key terminology and definitions. Additionally, throughout the subsections 5.2.1 to 5.3.1 the economic impact and importance of the new shared resource of the low-altitude is emphasised.

5.2.1 A Brief History of Airspace Structure

As the skies got busier after the second world war, the flight risk increased. A series of midair collisions, along with the advent of the jet era prompted the passing of the Federal Aviation Act of 1958 [75]. One of the outcomes of this Federal Act was the creation of the USA's Federal Aviation Administration (FAA) [159] which marked the beginning of a more complex system of airways. An initial structure divided the airspace into to main sections, the lower section of below 18,000 feet or 5486.4 meters, consisted of what were so-called *Victor Airways*, eight nautical miles or 14816 meters wide each, that were used by both pilots flying under Instrument Flight Rules (IFR) and Visual Flight Rules (VFR). A map of the air pathways would resemble a game of connect-the-dots in which each dot represents Very High Frequency (VHF) Omnidirectional Range station (VOR) that sends beacons up to the planes to assist navigation. Above the Victor airways were the *jet-ways*. This included the most restricted airspace, which would later become known as Class A airspace. Air Traffic Controllers (ATC) required all pilots to be instrument-rated at these altitudes, although improvements in VHF Omnidirectional Range (VOR) technology enabled them to map out their own routes independent of the established pathways.

Air traffic control (ATC) was on the way to become more automated thanks to advancement in electronics and introduction of computers [218]. On the other hand, with technological advancements, the cost of flying was reduced and hence aviation became more common and traffic demands increased that it effectively went out of control after the airline industry was deregulated in 1978 [208]. This created a highly competitive airline industry and led to the first National Airspace System (NAS) Plan in 1982 [212] that was designed to enhance air traffic control and air navigation in order to stay at pace with the rapid airline industry growth over the decades following [208]. Efforts to automate the system continued and in a matter of years the skies resembled an intricate latticework of specialised airways. These stretched laterally across the landscapes below and stacked up in layers, marking different vertical levels of restriction.

The most recent major adjustment to the airspace structure took place in 1993 [192] when the current system of airspace class came into force. The ever so slightly modified version of the international system divided the sky into a veritable layer cake of classes labelled A through G, based on altitude. Whereas Class A represented the strictly regulated jet-ways, Class G is completely uncontrolled. The description of the different classes is presented in subsection 5.2.2.



Airspace Classes Specifications based on ICAO

Class	Flight Rules	Controlled	ATC Clearance	Separation
A	IFR	Controlled	Required	Provided
B	IFR/VFR/SVFR	Controlled	Required	Provided
C	IFR/VFR/SVFR	Controlled	Required	Provided for IFR/SVFR
D	IFR/VFR/SVFR	Controlled	Required	Provided for IFR/SVFR
E	IFR/VFR/SVFR	Controlled	Required for IFR/SVFR	Provided for IFR/SVFR
G	VFR/IFR	Uncontrolled	Not provided	Not provided

FIGURE 5.1: Standard airspace classes.

5.2.2 Key Terminology and Definitions

In order to better put things in prospective, this subsection presents a set of concepts, terminology and definitions that are referred to throughout the remainder of the manuscript. The definitions are adopted from international standards and from the International Civil Aviation Organisation [303].

Airspace: in aeronautics, the airspace refers to the portion of the atmosphere that falls under the control or authority of the country above which it is located. Airspace over large surfaces of water can be referred to as Oceanic Airspace and usually lacks precise ground control.

Class A airspace: Class A airspace is generally the airspace from 18,000 feet Mean Sea Level (MSL) up to and including flight level (FL) 600 (c.f. Figure 5.1). Unless otherwise authorised, all operation in Class A airspace is conducted under instrument flight rules (IFR).

Class B airspace: Class B airspace is generally airspace from the surface to 10,000 feet MSL surrounding nations' busy airports in terms of either operations or passenger enplanements. The configuration of each Class B airspace area is individually tailored and generally consists of a surface area and two or more layers. Class B airspace often resembles an upside-down wedding cake (c.f. Figure 5.1). It is main design objective is to contain all published instrument procedures once an aircraft enters the airspace. An Air Traffic Controller (ATC) clearance is required for all aircraft to operate within this class to ensure separation within the airspace.

Class C airspace: Class C airspace is the airspace from the surface to 4,000 feet above the airport elevation surrounding those airports that have an operational control tower, are serviced by a radar approach control, and have a certain number of IFR operations or passenger enplanements (c.f. Figure 5.1). Although the configuration of each Class C area is individually tailored, the airspace usually consists of a surface area with a five nautical mile radius, an outer circle with a ten nautical mile radius that extends from 1,200 feet to 4,000 feet above the airport elevation, and an outer area. Each aircraft must establish two-way radio communications with the ATC facility providing air traffic services prior to entering the airspace and thereafter maintain those communications while within the airspace.

Class D airspace: Class D airspace refers to the airspace from the surface to 2,500 feet above the airport elevation surrounding the airports that have an operational control tower. Similar to Class C, the configuration of each Class D airspace area is individually tailored and when instrument procedures are published, the airspace is normally designed to contain the procedures. Arrival extensions for Instrument Approach Procedures (IAPs) may be Class D or Class E airspace. Unless otherwise authorised, each aircraft must establish a two-way radio communications with the ATC facility providing air traffic services prior to entering the airspace and thereafter maintain those communications while in the airspace (c.f. Figure 5.1).

Class E airspace: If the airspace is not any of the above classes yet is controlled airspace, then it is referred to as Class E airspace (c.f. Figure 5.1). Class E airspace extends upward from either the surface or a designated altitude to the overlying or adjacent controlled airspace. When designated as a surface area, the airspace is configured to contain all instrument procedures. Also in this class are federal airways, airspace beginning at either 700 or 1,200 feet Above Ground Level (AGL) used to transition to and from the terminal or en-route environment, en-route domestic and offshore airspace areas designated below 18,000 feet MSL. Class E has control services available, however, VFR pilots are not required to make any contact with ATC unlike in other controlled airspace.

Class G airspace: Class G airspace refers to the uncontrolled portion of the airspace (c.f. Figure 5.1). Class G airspace extends from the surface to the base of the overlying Class E airspace. Although ATC has no authority or responsibility to control air traffic, pilots should remember there are VFR minimums which apply to Class G airspace [2].

Flight Information Regions (FIR): A Flight Information Region (FIR) is an airspace of defined dimensions within which flight information service and alerting service are provided.

Flight Information Service: A Flight Information Service is a service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flights.

Alerting Service: Alerting service is a service provided to notify appropriate organisations regarding aircraft in need of search and rescue aid and to assist such organisations as required.

ATS Route: An ATS route is a general term referring to specified route designed for channelling the flow of traffic as necessary for the provision of air traffic services whether airway, advisory route, controlled or uncontrolled route, arrival or departure route.

Airways: An airway or flight path is a designated route in the air. They are defined segments within a specific altitude block, corridor width, and between way-points based on geographic coordinates named fixes.

Fixes: A fix is a way point within an airway based on known geographic coordinates.

Prohibited and Dangerous Zones: A prohibited zone is restricted portion of an airspace defined by specific limits in which flying is totally prohibited except for authorised military and government flights. On the other hand an active dangerous zone is an airspace of defined limits in which dangerous activities for aircraft may develop during a specific time frame. Examples of such activities may include test flights, parachuting or space rocket launching.

5.2.3 Influence of Airspace Structure on Traffic Management

Whether for manned or unmanned aviation, air traffic performance is not only subjected to traffic demands but also dependent on the given airspace structure. The flow characteristics of the airspace including traffic volume, mix of aircraft types, flight activity, climbing and descending traffic including Vertical Take Off and Landing (VTOL), best angle, best rate, recommended climb for visibility and engine cooling, cruise, glide and powered descent to name a few, all influence airspace complexity, which in turn can influence the probability of safety occurrences [232]. In other words, all these dynamic and static complexity components potentially have an impact on the safety of the air traffic management system or UTM in our case.

As the number of UAVs continues to grow and given the nature of the major application domains, the demand for utilising the low–altitude airspace will only be expected to expand. In [286] the authors argue that the difficulty of safely separating a large number of UAVs can be simplified through the system design of the airspace structure. However, in contrast to civil manned aviation, there is, until this day, no clear consensus on how the low–altitude airspace should be structured. Over the recent few years, the topic has gained attention of the scientific community in turn leading to a handful of articles presented addressing the aforementioned topic. On one hand, some articles emphasise that a well–defined, structured approach is necessary to account for the expected high traffic densities [7, 238] and on the other, some diminish the need for a well–structured airspace based on the argument that a free flight systems without any fixed structure would enable UAVs to take user-preferred direct routes and that even if that comes at the cost of higher risk of conflict or collisions under high traffic demands [286].

For the former approach, studies state that it is required that UAVs have pre–planned conflict free routes negotiated and pre-approved between the UAV or UAV operator and Air Navigation Service Providers (ANSPs). In addition to the three-dimensional (3D) paths that aircrafts are required to follow, the negotiated and approved trajectories include fixed time constraints for arrival at the different way-points along the pre-approved route. In such approaches, the position-related uncertainties of aircrafts can be minimised, in turn, allowing for minimising the safety distance required between different trajectories, hence, enabling an increase in traffic capacity levels. On the contrary, free flight studies have found evidence of the opposite. The concept of having free flight UAVs has been shown to allow for higher traffic densities by reducing traffic flow constraints and structure according to [102, 161]. In such approaches, UAVs are allowed to fly on operator–preferred, often direct air routes, while separation responsibility is delegated to each individual UAV by means of on–board collision detection and resolution systems. As a result, the authors argue that traffic would be evenly distributed over the airspace, thus reducing the number of potential conflicts while increasing capacity [103, 135]. However, this free flight mode comes with multiple challenges of its own when considering the ripple effect of rapid unexpected changes in flight paths within large traffic densities possibly due to rogue behaviour. On one hand, as illustrated in Figure 5.2, a free flight system without any structure would enable UAVs to take user-preferred direct routes at the cost of higher risk of conflict or collisions under high traffic demands similar to civil manned aviation prior to 1958 and on the other, an extremely structured airspace could lead to poor operational efficiency [287] specifically when UAVs follow predefined routes following ANSP defined way-pints [286].

To this end, it is clear that the Class G airspace structure plays a significant role in the traffic management at a strategic but also tactical level in terms of CD&R.

5.3 Proposed Low-Altitude Airspace Structure

As briefly explained in section 5.2, ICAO [303] divides the world's navigable airspace into seven, three-dimensional (3D) segments, represented by the first seven letters from the ISO basic Latin alphabet. All segments are controlled and regulated by Air Traffic Controllers (ATCs) except for the lower-most one, known as Class G. The latter ranges from 0 to 700ft AGL and remains uncontrolled [281] except in the close proximity of published airports. With the expected rise in the number of UAVs requesting to operate within Class G and motivated by the evidence of the impact of airspace structure on traffic management, this section showcases the recent development in terms of spatial-design and structure of the low-altitude airspace as well as present the proposed a novel Class G structure and formal model.

As UTM-related research continues to develop more researchers realise the importance of investigating the most appropriate structure for the low-altitude airspace. The recent work in [286] and further extended in [281] presents different categorisation of airspace structures from literature ranging from no structure to highly structured tube-like models as explained bellow and summarised in Figure 5.2.

Free Flight concepts, as explained in [286], extend civil manned aviation proposed conceptual models of ATM by introducing decentralised control relying on the advancement in aircraft technologies. Such concepts can be loosely described as unstructured airspace. In *free flight* concepts, UAV traffic is solely subjected to physical operational constraints. As traffic demand is often unstructured, the free flight concept assumes that any structuring of traffic flows would lend to decreasing the overall global efficiency of traffic and that safety is ultimately improved by dispersing traffic over the airspace, in turn, resulting in self–risk mitigation. In [286] the authors refer to this as the *Full Mix* and argue that when using such airspace model, UAVs will be permitted to fly direct paths from origin and destination, at their optimum flight altitudes and lateral velocities. Since such flight concept imposes no restrictions to the flight path of a UAV, it is therefore crucial that every aircraft has reliable conflict resolution system to reduce collisions and to minimise deviations from optimal flight route or path.

Layered Structures segment the airspace into vertically stacked heading bands, where each altitude layer limits horizontal travel to within an allowed heading range similar to structures used in manned aviation. According to [286], *layered structure*, are expected to reduce the probability of conflicts by limiting the relative velocities between UAVs flying at the same altitude segment. However, this increased safety comes at the price of efficiency; while direct horizontal routes are still possible, the vertical flight profile of the path is dictated by the relative bearing between origin and destination and the corresponding altitude band with the required heading range. Therefore, UAVs may not be able to operate at their optimal altitude and velocity, resulting in higher energy consumption. An exception is made for climbing and descending aircraft; these aircraft are allowed to maintain heading while climbing or descending to their destination altitude.

Zoned Structures in many ways similar to layered structures, the zoned airspace structures segment UAV traffic based on similarity of travel heading or direction [286]. However, while the layered structures handled traffic vertically irrespective of city topology, the zoned structures take into account the layout of the city in its topology. In such concept structures, two main components exist; first, the circular directional paths that resemble ring roads in ground vehicle traffic systems; and second the radial connections that interconnect the concentric circular paths.

Tubed Structures offer the highest level of structuring out of all concepts presented in [281]. Such concepts implement air like highways referred to as tubes that provide a fixed route structure in the air. [286] explain that the main goal behind tubed structure concepts is to increase predictability of traffic flows by means of fixed, preplanned conflict-free routes.

To this end, it is clear from the taxonomy is that every structuring concept comes with advantages as well as distinct limitations. It can be inferred that in order to have an efficient and safe fully distributed UTM, a novel low-altitude Class G airspace structure needs to be devised, one that combines elements from the different concepts presented in literature but also aligns with existing and ongoing aviation standardisation activities.

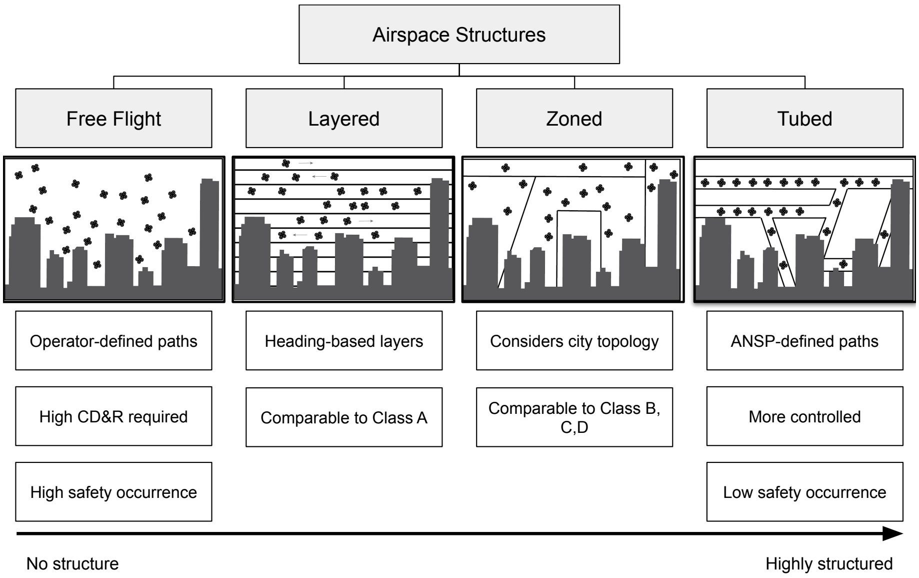


FIGURE 5.2: Illustrative taxonomy of airspace structures.

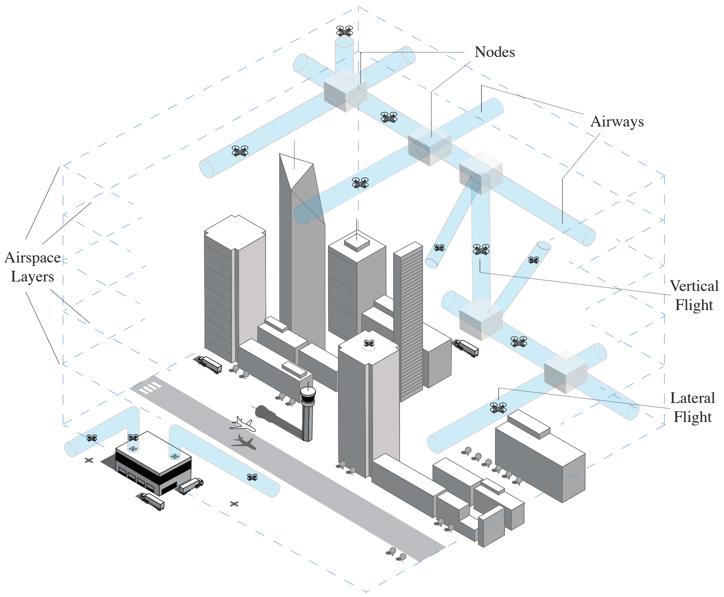


FIGURE 5.3: Proposed multilayer Class G airspace.

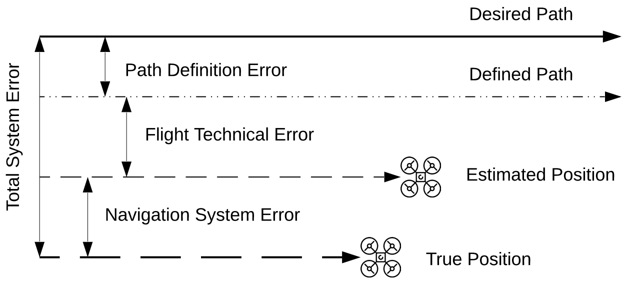


FIGURE 5.4: Total System Error of a UAV.

5.3.1 Devised Class G Schematic Model

As the previous sections emphasised a novel Class G airspace is a mandatory first step towards a distributed UTM. Motivated by the limitations of the existing concepts, this subsection presents our proposed novel schematic model of the low-altitude airspace known as Class G as well as a corresponding set of definitions and terminology to complement those presented in section 5.2.2. The proposed model aims to combine the benefits of free flight concepts in terms of traffic capacity sizes and optimal/near-optimal paths with the control and safety benefits of tube structures while maintaining some key elements adopted in Classes A through D such as headings and zones. In other words, a structure that allows for the potential large number of autonomous UAVs to operate while aligning to regulatory frameworks of U-Space and UTM system.

In our proposed model, illustrated in Figures 5.3-5.5, we further divide the Class G airspace into 3D horizontal segments, referred to as layers, at different operational altitudes with separation allowing safe UAV flight. This extends a variation of the hemispheric rule [303] to Class G, however, in this layered approach, the separation between layers is guided by the *Containment Limit (CL)* of the largest UAV allowed to fly within that specified zone within Class G. This can be derived from the Total System Error (TSE) of that UAV, illustrated in Fig. 5.4 and further explained in section 5.3.1.

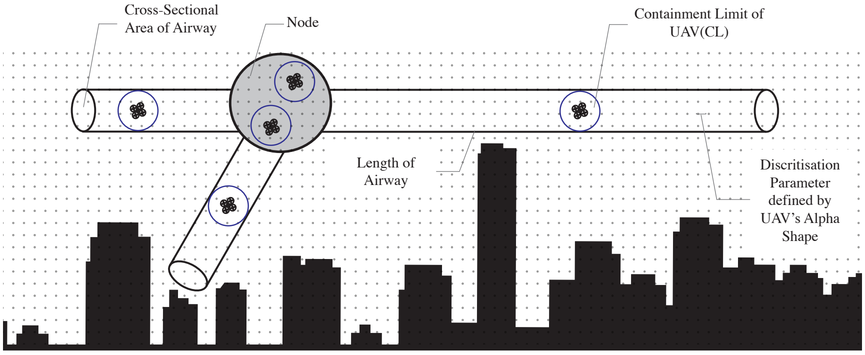


FIGURE 5.5: Airways and nodes in proposed model.

Then following the approach presented in [33], a city's elevation map can be discretised using a topological analysis into a data-set of static-obstacle-free points within the different layers. This is key for structured airspace design and path planning. The level of detail of the discretised airspace is defined by the volume representing the UAV (alpha shape) as explained in [55]. This can be referred to as the airspace availability assessment stage and it adheres to the framework proposed in [33], a formal representation of which is adopted as is from literature and summarised below.

Let Γ represent the discretised 3D data-set lattice of the airspace zone of interest with a unit cube of size ϵ.

$$\Gamma = \left\{ g_{lmn} : 1 \le l \le N_x, 1 \le m \le N_y, 1 \le n \le N_z \right\}$$

We can define the three subsets of Γ according to [33] follows:

$$\Gamma_o = \{ g_{lmn} \in \Gamma : g_{lmn} \text{ occupied by static obstacles} \}$$

$$\Gamma^{\delta}_{out} = \{ g_{lmn} \in \Gamma : g_{lmn} \text{ geo-limit of size } \delta \}$$

$$\Gamma^{r}_{in} = \{ g_{lmn} \in \Gamma : g_{lmn} \text{ alpha shape of radius r } \}$$

When a cell in the grid is occupied by a static obstacle or when zoned by geo-limit that cell is considered closed or unavailable. Where the availability of $cellg_{lmn}$ can therefore be defined as the indicator function:

$$cell(g_{lmn}, \delta, r) = \begin{cases} 0, & g_{lmn} \epsilon \Gamma_o \cup \Gamma^{\delta}_{out} \cup \Gamma^{r}_{in} \\ 1, & otherwise \end{cases}$$

Then the usability U of Class G airspace at altitude layer k can be defined as:

$$U(k, \delta, r) := \frac{\left(\sum_{1 \le l \le N_x, 1 \le m \le N_y} cell(g_{lmn}, \delta, r) \right)}{N_x \times N_y}$$

The resulting volume of obstacle-free space is referred to as the *usable urban airspace* which is the shared resource that is utilised by the UAVs. The latter comprises of *Airways* and *Nodes*, airways being corridors connecting nodes within a layer (horizontal) or between layers (vertical or diagonal). Airways allow UAVs to fly without direct communication with the UTM, guided only by the rules of the airway

(velocity limits, flight headings and maximum traffic capacity) and information exchanged between UAVs through ad-hoc communication. Airways' cross-sectional size is defined by the UAVs' CL, while their lengths is defined by the segment's static-obstacle-free space as well as airway-intersections, referred to as nodes (cf. Fig. 5.5).
Within nodes, UAVs can change their *Flight Mode*. In our devised model, three main flight modes are considered, *lateral flight*, *vertical flight* and *hovering* for multi-rotor UAVs. Additionally, within the proposed Class G structure, the different airspace layers allow different velocity ranges, that increase with altitude. This is supported by the argument that higher altitudes contain less static obstacles [33] and hence, longer airways are possible. UAVs rely on ad-hoc communication to exchange dynamic traffic information such as their flight velocities and airway traffic density. This in turn reduces latency and allows UAVs to make local routing decisions through the airspace eliminating the need for continuous direct communication with a centralised UTM.

Complementary Terminology

In order to better put things in perspective, we introduce a set of model-specific concepts and definitions that complement those presented in section 5.2.2 and explain how they are related to one other.

Urban Airspace: The *airspace* as defined in section 5.2.2 as the shared resource that is utilised by the aircrafts and more specifically UAVs when talking about Class G airspace. In our proposed model, we use the term *urban airspace* to refer to the very low-altitude airspace over populated cities representing the high risk shared operational segment of Class G. Within our schematic structure, the urban airspace can be seen as a virtual/digital resemblance of the roads network in cities but with the added complexity of three dimensional layers.

Airway and Flight Corridor: With a similar function to UAVs as roads and highways are to cars, we define *Airways* or *Corridors* (*Airway* segments) as passages through which a UAV can fly between nodes without direct communication with a traffic management system, but only guided by the rules of the airway. Such rules include the allowable velocity ranges, flight directions and maximum traffic capacity. The size and shape of the corridor is defined based on the *Containment Limit* of the UAV, as explained above.

Containment Limit (CL): The *Containment Limit* of an aircraft is explained by ICAO as the volume defined by a *Containment Radius (Rc)* which is the radius of the volume where there is a 95% probability the aircraft is within, at any given time of its stated position, both horizontally and vertically as illustrated in Figure 5.4 [34] [267]

Node and Intersection Node: *Nodes* are points that connect airways to other airway or airways, in the case of an *Intersection Node*. Within nodes, UAVs are allowed to change their *Flight Mode* and change airways or corridors.

Flight Mode: Three main *flight modes* are considered: *lateral flight*, *vertical flight* and *hovering* for multirotor UAVs. In cases where a UAV is not obliged to comply with a specific mode, it is referred to as in a state of *free flight*.

Flight Path: A *Path* is a complete route from start to destination, through different nodes and corridors.

Optimal Lateral Velocity: The *Optimal Lateral Velocity* is the velocity at which the UAV is most energy efficient benefiting from *transitional lift* which is the lift gained when a UAV translates from a hover into lateral flight.

Transitional Lift: *Transitional Lift* is the lift gained when a UAV translates from a hover into lateral flight; additional lift increases with increasing airspeed and is derived by the rotor system moving into undisturbed air.

5.3.2 Proposed Class G Formal Model

The problem naturally lends itself to a modelling as a graph structure similar to a road network, however, with added complexity of dynamic and multilayered as explained throughout this section.

One particularly useful way to study complex systems is by analysing the networks that encode the interactions among the system's elements. However the complexity of some real systems is such that it is not possible to study them as single layer networks. To account for this complexity, a more general framework, known as multilayer networks is considered.

Over the recent years, research in physics and computer science developed different notions and models for complex networks referred to as networks of networks [41], multilayer social networks [185], and interconnected networks [49] to name a few. The literature provides many applications for such systems in ecology [234], biology [82] and economic applications [213], but what interests us most are those addressing game theory [20] and transportation [73].

Transportation systems are one distinct example of systems where the multilayer formulation arises in a natural way [73] as there can be multiple modes of transport between given locations. This can be represented as a multilayer network where each layer is a representation of one mode of transportation forming an already complex network. It is thus necessary to distinguish each of them when studying the whole system [73]. In [30] the authors follow this approach to model the European air transport system as a multilayer network where each layer represent an airline. Similarly, [104, 294] analyse, respectively, the structure of the Greek and Chinese air transportation networks using the same multilayer framework.

However, in comparison, our contribution expands this methodology to represent the Class G airspace as a multilayer network. Here each layer represents, not airlines, but different segments, later referred to as *paths*, that vary in properties such as *allowable velocity*, *energy consumption* and *traffic capacity*, which, to the best of our knowledge, has never been proposed in the air traffic management literature

Multilayer Class G Network Model

We propose to model of the Class G airspace as a multi-weighted multilayer network, M_{ClassG}, where:

$$M_{ClassG} = (G_M, N, W_E)$$

The airspace contains a non-empty set of layers N, each layer being represented as a graph of nodes and airways $G_M = (V_M, A_M)$. Nodes can belong to one or more layers.

$$V_M = \bigcup_{\alpha=1}^{|N|} V^{\alpha}; \alpha \in N$$

Each edge, i.e. airway, is assigned different weights defining the various traffic rules such as headings and maximum velocities. For example, in the first stage of model verification simulations, these included three weights corresponding to travel time, energy cost and traffic capacity respectively: $a_M = (u, v, \alpha, t, e, c)$ with $u, v \in V_M$, $\alpha \in N$ and $t, e, c \in W_E$, a non-empty set of weights at event step, E.
The set of edges is composed of intra-layer edges, i.e., airways within one layer (A^{α}), and inter-layer edges, i.e., airways connecting layers ($A^{\alpha,\beta}$), with $\alpha, \beta \in$ N.

$$A_M = \Big(\bigcup_{\alpha=1}^{|N|} A^{\alpha}\Big) \cup \Big(\bigcup_{\alpha,\beta=1,\alpha\neq\beta}^{|N|} A^{\alpha,\beta}\Big),$$

with $A^{\alpha} \subseteq V^{\alpha} \times V^{\alpha}$, and V^{α} a finite, non-empty set of nodes on layer α, and $A^{\alpha,\beta} \subseteq V^{\alpha} \times V^{\beta}$; with $\alpha, \beta \in N$, $\alpha \neq \beta$ and V^{β} a finite, non-empty set of nodes on layer β.
Based on the definition in [274] each layer is considered an incremental network where link weights are dynamic, that is, the structure of the network remains as is, but the weights vary over time. Figure 5.6 is an illustration to a small instance of an airspace network.

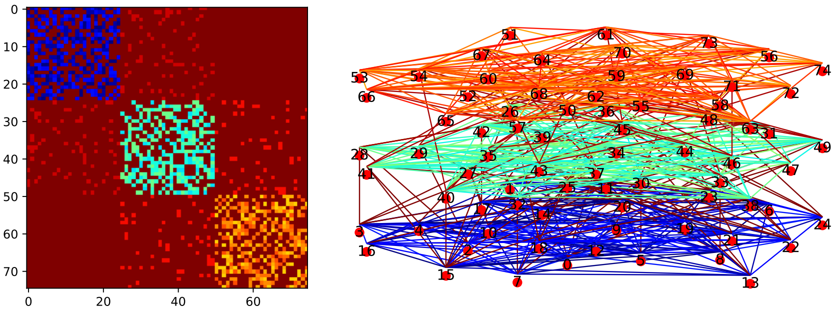


FIGURE 5.6: Example of airspace network..

5.4 Application Scenario and Operational Example

To consolidate the model's description, this subsection narrates one operational example relying on the proposed multilayer model of the Class G airspace. However, our proposed model can lend itself to multiple other scenarios.

Considering two groups of UAVs, the first one is on a routine mission such as monitoring and data collection, while the second group consists of emergency intervention UAVs such as medical rescue UAVs. Both groups entering the *airspace* have different mission priorities and incentives to get to their destination. UAVs enter *airways* through different *nodes* and traverse from origin to destination along *paths* at different layers. Each altitude segment, referred to as layer, allows different velocity ranges that increase at higher altitude layers. We assume that higher altitudes offer shorter travel times at the cost of higher energy consumption.

As each UAV traverses the network, it communicates and exchanges information with other UAVs at network *nodes* within its range in an ad-hoc manner. Based on the exchanged traffic parameters information and rules such as density and minimum flight velocities, UAVs make local routing decisions to switch between *airways*, airspace layers and *flight modes* according to their respective objectives of minimising time of flight or energy consumption. In this operational example, UAVs follow an initial operator-preferred pre-defined paths and as they traverse the available urban airspace towards their respective destinations, they adapt and sometimes change their flight parameters and paths to better optimise their objectives. This in turn combines the benefits of free flight, zoned, layered and tubed structures in a more dynamic model.

5.5 Summary

In order to be able to devise a fully distributed UTM that allows UAVs to exchange information and dynamically optimise their flight paths in response to the changing conditions, a corresponding adaptable structure of the airspace is paramount.

As Chapter 4 highlighted that the role of a UTM can be addressed over two subsequent management stages, strategic airspace management and tactical airspace management. Where section 4.2.1 of the latter explained the role of strategic airspace management in efficiently planning and segmenting the available low-altitude airspace with the main goal of making optimal use of the shared resource. Such efficient airspace management builds on a suitable airspace structure as emphasised in section 5.2.3 of this chapter.

To this end, Chapter 5 presented novel low-altitude airspace schematic and formal structural models building on the latest works in scientific literature and technical standardisation. The proposed Class G structure and the corresponding terminology and model outlined in section 5.3 can be seen as a virtual/digital resemblance of the roads network in cities but with the added complexity of three dimensional dynamic multilayers.

The absence of physical infrastructure in contrast to tunnels, bridges and highways in vehicular networks, further convoluted by the higher degree of mobility of UAVs and the centimetre or even sub-centimetre position precision requirements, mean that there will be a greater reliance on information exchange for tactical airspace management when compared to road vehicles. Chapter 6 hence, builds on the work presented here extending the tactical airspace management aspect of UTM by exploring the UAV connectivity infrastructure and devising an information exchange framework.

End of Chapter 5

Chapter 6

Information Exchange Model

6.1 Introduction

Having a low-altitude Class G airspace structure that takes into consideration the future traffic demands of UAVs and account for their operational requirements, limitations and expected autonomy developments is the first foundational step towards building a distributed UTM, with the second being a corresponding information exchange model. The novel Class G structure and the corresponding formal model proposed in Chapter 5 present a novel virtual structure without a physical infrastructure. Such low-altitude airspace structural design can be thought of as a digital resemblance of the roads network in cities but with the added complexity of three dimensional dynamic multilayers.

The absence of a physical infrastructure in contrast to tunnels, bridges and highways in vehicular networks, further convoluted by the higher degree of mobility of UAVs and the centimetre or even sub-centimetre position precision requirements, mean that there is a greater reliability and accountability on near real-time information exchange for tactical airspace management when compared to road vehicles. To this end, Chapter 6 builds on the novel structure by devising an information exchange framework to address the tactical airspace management aspect of UTM. While communication is a well-established domain and falls out of scope of this thesis, throughout the following sections of this chapter of the manuscript we explore and highlight some of the significant UAV communication concepts in literature international technical standards.

In this context, the chapter is structured as follows. Section 6.2 revisits and further explores the critical role of tactical airspace management in a successful UTM. The section investigates the correlation between tactical airspace management's role in handling dynamic traffic optimisation and emphasises the need for efficient information exchange. Section 9.2.2 presents our devised information exchange framework that allows autonomous UAV operation by enabling a hybrid and decentralised

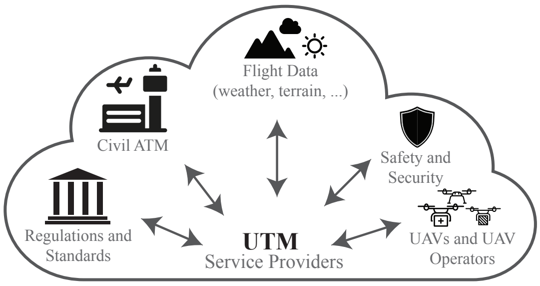


FIGURE 6.1: Illustration of the role of UTM in information exchange.

information exchange through UAV-to-UAV and UAV-to-Infrastructure communication. State of the art and recent technical standardisation efforts in UAV communications is explored in Section 6.4 additionally, the section highlights key challenges in existing protocols and models. Finally, Section 6.5 summarises the chapter.

6.2 Tactical Airspace Management

While strategic airspace management discussed in Chapter 5 addressed the definition of the airspace policy and establishment of a novel structure including allocation of airspace according to mission requirements as well as predefined routes, the tactical airspace management handles real-time use of the shared airspace resource allowing safe UAV operation and deconfliction (further explored in Chapter 7).

The tactical airspace management aims to address the complexity of real-time operations and use of the low-altitude Class G by striving to achieve two main goals, firstly, mitigating collision risks by maintaining separation between the airspace users, this includes both manned or unmanned aerial vehicles in addition to others such as space vehicle launch or re-entry [169]; secondly, handling the dynamic aspect of operation by meals with tactical re-routing and capping of flows away from capacity problem zones [56]. In other words, tactical airspace management is the responsive dynamic complementary management level to the strategic airspace design and with advancements in computing paradigms and autonomous systems, its functions will continue to extend beyond a centralised authority to a more resilient distributed alternative on a UAV level.

In line with what the authors in [56] highlight on the role of tactical airspace management for a more dynamic ATM, our work extends a similar emphasis for UAV traffic management as well as for the interfacing between unmanned and manned aviation. To this end, it is of paramount importance to the success of a tactical system that the heterogeneous airspace users and stakeholders have access to updated information in order to facilitate safer and more efficient operations. The transition from strategic to tactical management of airspace is hence contingent upon robust and reliable information exchange and therefore an efficient underlying Flight Information Management Systems (FIMS) is crucial.

6.3 Flight Information Management System

A Flight Information Management System (FIMS) facilitates the exchange of support and traffic data including 3D positions, heading, velocities weather information as well as other critical and supporting data between airspace users, Air Navigation Service Providers (ANSPs) and other authorities as illustrated in Figure 6.1. Such exchanged information and data is used to provide situational awareness, issue traffic alerts or geo-limitation warnings to operators for example. FIMS is therefore considered at the heart and core of a successful UAV traffic management system's safety, support as well as supplementary functions as detailed in Section 4.3 of Chapter 4.

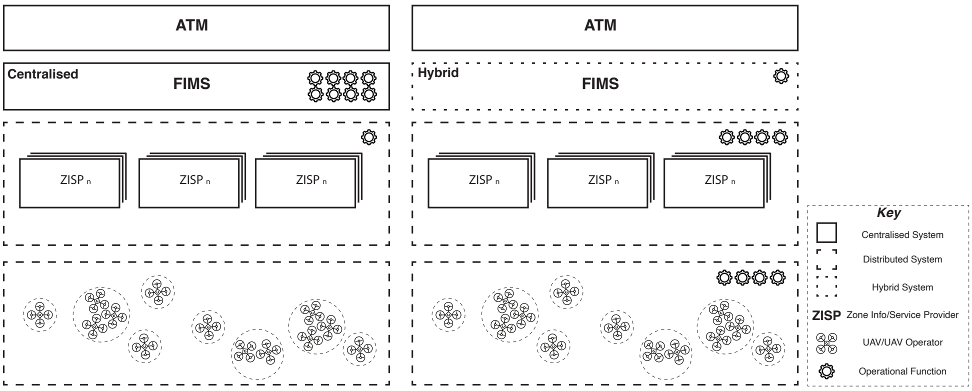


FIGURE 6.2: Illustration of centralised versus hybrid FIMS functional distribution.

To this end there is not yet one unified definition of FIMS, however, for the purpose of this manuscript we define it as a mechanism of gateways for data exchange between UTM stakeholders and ANSPs, through which authorities can provide directives and make relevant National Airspace System (NAS) information available to UAV operators, on one hand, and as a gateway for authorities to access information about on-going and up-coming aerial operations as well as any situations that could have an impact on the shared airspace, on the other. Figure 6.2 illustrates the responsibility distribution load in i) a centralised FIMS, vs. that in ii) a hybrid structure. While the centralised structure could be comparable to the centralised Common Information Service (CIS) in civil aviation, a hybrid approach provides several advantages in terms of clearly assigning and controlling the safety–critical airspace management functions in an unambiguous and efficient manner, thus reducing the need for complex information exchange requirements.

6.3.1 Proposed Information Exchange Model

To this end, we propose a possible information exchange model based on the hybrid FIMS approach to comply with the envisioned UTM. Figure 6.3 presents an illustration of the proposed approach where ATM functions - centralised architecture - interface with a distributed UTM through the integration functions. In the proposed model, UAV traffic management functions follow a federated approach through the different Zone Information and Service Providers (ZISPs). Here each airspace is served and managed by multiple, possibly competing, providers of services and supplementary information who are collectively responsible for the safety as well as compliance within their serviced zone.

Additionally, due to the high mobility of UAVs in flight, the model considers UAVs to communicate together UAV-to-UAV (U2U) and to the infrastructure (U2I) in an ad-hoc manner, similar to the communication model proposed in [167, 191].

A simplified view of the different types of communicated messages is presented in

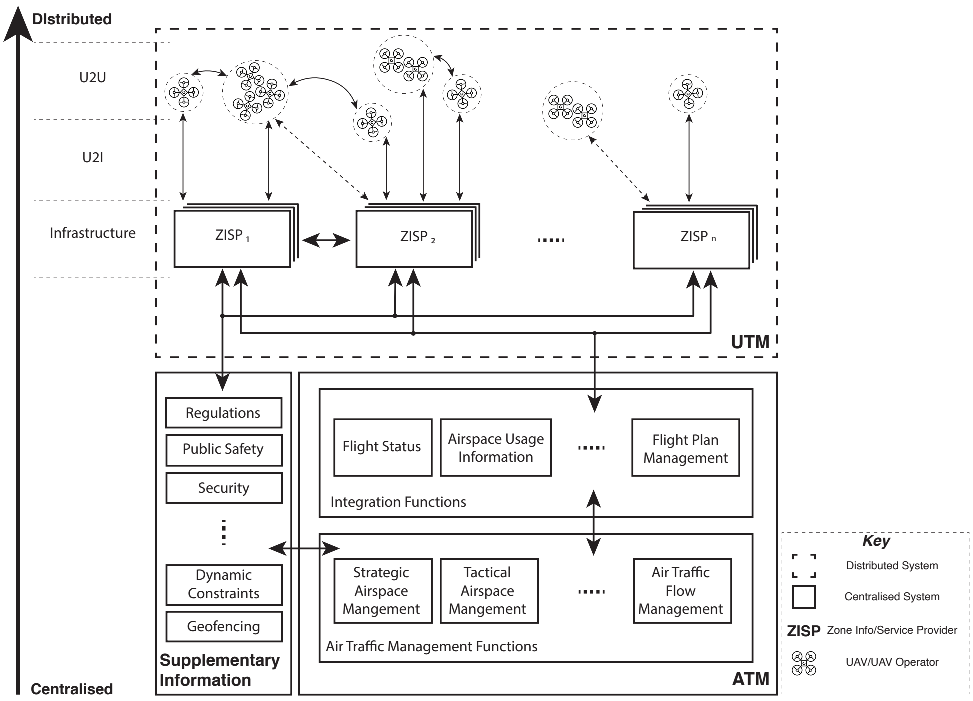


FIGURE 6.3: Information Exchange Model for dUTM.

Figure 6.4 based on [264]. In the same article, the authors firstly categorise the types of communicated messages based on their repetition rate and size then compare the communication performance of a centralised and a distributed UTM in a conflict detection and resolution scenario.

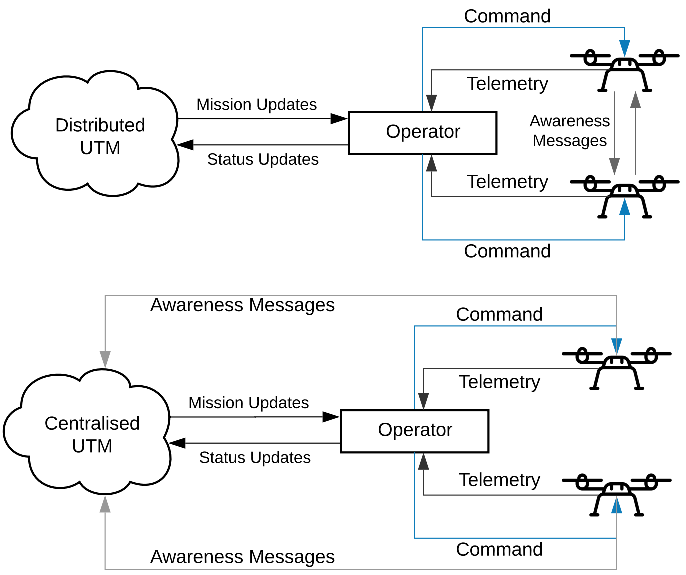


FIGURE 6.4: Communicated messages in a distributed (top) and centralised (bottom) UTM [264].

In the proposed information exchange model, each UAV is considered a flying node in a Flying Ad-hoc NETwork (FANET) with some acting as gateways, as previously explained in Chapter 3 and illustrated in Figure 3.6 – *on UAVs as part of the IoT architecture*, to relay communicated information as explained in [175]. UAVs exchange information between them using standard IoT communication protocols [167, 175] at predefined time intervals, similar to automatic dependent surveillance-broadcasts and at node locations within the network. The broadcast is composed of the UAVs' identification, lateral flight velocity, location and timestamp. With reference to Figure 6.4, in our envisioned information exchange model, UAVs rely on such communicated awareness messages for deconfliction as well as to locally evaluate traffic conditions in airways and make local optimisation-related routing decisions.

However, as the airspace will be shared among various users from UAVs to unpowered aircrafts (hang gliders, para-gliders, balloons, etc.), helicopters, jet-propelled planes and even space rocket launch/re-entry [169], for efficient management of operations and for better risk mitigation, information not only has to be well communicated, but also shared quickly enough to be actionable as emphasised in [169].

On account of this, FIMS has to incorporate different sources of communication of data including standardised technologies already used within manned aviation [74]. In consideration of that, technologies such as 5G and Long–Term Evolution (LTE) can be used for UAV–based communications in lower airspace over cities, and possibly fused with European Aviation Network (EAN) position information and date provided by FLARM – *for light aircrafts*, Automatic Dependent Surveillance Broadcast (ADS-B) or Very High Frequency band (VHF) air-ground Digital Link (VDL) – *proposed by ETSI*, to improve situational awareness. To this end, we emphasise that a successful implementation of tactical airspace management will require accounting for communications protocols of different stakeholder.

6.4 UAV Communications

Although, there are existing – *however legacy* – standardised communication protocols and technologies used within manned aviation, UAV communication technologies and standards are lagging further behind. While 5G and LTE are potential candidate solutions, they each come with a set of challenges when considered within the autonomous UAV domain, mainly due to the demanding communication requirements of such wireless mobile aerial robots.

According to IEEE's technical committee on networked robots [115], a wireless networked robot system (WNR) is a subset of wireless sensor and actuator networks (WSANs). Such a system can be identified by two elements: i) autonomous capabilities and ii) network-based cooperation. The first refers to the necessity, for a robot, to autonomously move and interact with the physical environment; while the second refers to its capability of communicating with others using radio technology. Over the recent years, the interaction between IoT and FANETs has become an important topic of research [209, 330]. The interested reader can find a detailed analysis of such communication protocols in [87, 167, 224].

6.4.1 Challenges in Existing Systems

UAVs operations need wireless connectivity for communication among UAVs as well as with infrastructure and other airspace users. As described in Section 6.3 such communications are paramount in order to mitigate risks and effectively manage the airspace by disseminating information in a highly dynamic environment. UAVs pose strong constraints regarding communications in contrast to other mobile WNRs some of these are result of their:

- degree of operational freedom and high mobility,
- continuously changing network topology,
- payload limitations,
- battery and energy constraints.

The used wireless communication technologies must therefore accommodate such operational constraints and be able to provide energy-efficient and low complexity and latency communication backbone to be deployed on large scalable UAV networks. While there exists some low–energy consumption robotic communication technologies such as ZigBee, RFID, or Bluetooth, that can be adapted for simple UAV applications, most these technologies work over relatively short distances and at low data rates. On the other hand, standards like LTE and WiFi work over long distances and provide an improved throughput, however they consume more energy, and demand comparably expensive fixed infrastructure of base stations with adequate link to the underlying network backbone. Scientific articles such as [316] present field trial results collected in LTE–Advanced networks and present insights into the capabilities of the current 4G+ networks for connected UAVs. Additionally, the work explores how 5G networks can further support diversified UAV operations. This is further complemented by experiments presented in [97]. Here the authors survey and quantify quality-of-service (QoS) requirements as well as data and network requirements for various UAV missions and assess connectivity, safety security and privacy.

Privacy, Security and Data Protection

In addition to the above mentioned issues, as UAVs continue to expand within IoT, they can be seen as smart connected devices and so inherent some of the challenges of other connected WSN devices. Most sophisticated applications require UAVs to collect large amounts of data, most of which is usually very sensitive, sometimes even safety-critical. Further convoluted by the lack of standards and by either legacy underlying technical systems and communication backbone or vulnerable alternatives adopted from manned aviation like ADS-B. Such data becomes a coveted target for cyber-attacks especially during exchange and regular update processes. For these data, protection from unauthorised access, misuse, and manipulation is paramount as explained in Section 3.4.3.

To this end, U2U and U2I communication remain an open issue due to the lack of a specific technology for support as well as the limitations of existing technologies that are not fully adaptable to the constraints and requirements of UAVs operations. It is therefore, of critical importance that new standards, specific for UAV communications be introduced in order for the full potential of these smart flying devices and platforms be realised.

6.4.2 Role of Technical Standardisation

Chapters 2 and 3 of this manuscript emphasised the role of technical standardisation in the development and advancement of technologies, specifically in emerging computing paradigms and more precisely when addressing security, privacy and data protection in IoT and UAVs in the latter. The recent few years have witnessed an undeniable digital transformation within the aviation sector and the emergent of several SDO working groups to tackle pressing standardisation challenges from 3GPP, ITU-T, ISO and IEEE. A similar trend is observed within the scientific research community, where recent works have continued to emphasise the need for UAV standards development.

Communication within aviation and especially within UAVs is a clear example. In [97] the authors present a summary of IEEE WiFi protocols and standards they additionally motivate and emphasise the need of rapid standards development of UAV–specific communication protocols. Similarly, the interested reader can find recent surveys on latest scientific and standardisation development in UAV communication in [71, 89, 327] to name a few.

6.5 Summary

To this end, Chapter 6 presented, in the above sections, a novel information exchange model based on a potential hybrid FIMS approach as a foundation and backbone to the tactical airspace management level to complement the strategic airspace design devised in Chapter 5.

The work additionally addressed the importance of communication for UAVs to operate within a network of digital/virtual airways in contrast to a physical network infrastructure such as tunnels, bridges and highways in vehicular networks, further convoluted by the higher degree of mobility of UAVs and the sub-centimetre position precision requirements. Furthermore, we highlighted the importance of efficient and secure data and information exchange and concluded that lack of UAV-specific communication international technical standards contributes significantly to the obstruction of global harmonisation.

Chapter 7 hence, builds on the work presented here devise a traffic optimisation and deconfliction model and present a set of approaches to tackle the multifaceted NP-hard path optimisation problem at strategic and tactical levels.

End of Chapter 6

Chapter 7

Traffic Optimisation Model

7.1 Introduction

One of the critical functions of a successful UAV traffic management system is to ensure efficient operations within the airspace. With the expected increase in UAV traffic demands over the coming few years, the devised distributed UTM should rely on UAVs autonomous capability of intelligently planning and optimising their collision–free paths relying on local knowledge gained via digital stigmergy. While path optimisation is a problem well-addressed in robotics literature, most presented solutions are either computationally complex centralised approaches or ones not suitable for the multiobjective requirements of most UAV use-cases.

To this end, the main contribution of this chapter is addressing the UAV traffic optimisation problem by tackling path optimisation and deconfliction simultaneously in a novel approach. The work builds on the distributed UTM airspace structural model and information exchange model presented in Chapters 5 – 6 and is structured as follows. Section 7.2 presents an overview of traffic flow theory models and key concepts that will be referred to throughout the work. Section 7.3 explores state of the art in robotic path planning. Section 7.4 presents the proposed traffic optimisation and deconfliction model, followed by the two stages of optimisation in Section 7.4.2 and Section 7.4.3 respectively. Finally, Section 7.5 summarises the proposed novel approaches.

7.2 Theory of Traffic Flow

While UAV traffic flow is a new uncharted research field, vehicle transportation engineering and design is a well-established domain that builds on decades of research. In this context, we adopt some of the key concepts of vehicle traffic flow theory to aid in our UTM traffic optimisation modelling.
To this end, the majority of traffic modelling theories are derived from the statistical theory presented by Greenshields in 1935 [84]. However, since then and several other traffic models have been presented in literature [200].
These models can generally be divided under the following three main categories:

- *Microscopic* – traffic is modelled as movement of individual vehicles [84];
- *Mesoscopic* – traffic is modelled as an interaction between vehicle groups;
- *Macroscopic* – traffic flow is modelled as a continuous fluid [83].

As explained in [83] with increasing traffic demands it is crucial to understand traffic flow dynamics and hence the authors proposed the foundation of macroscopic flow modelling. The work assumed large traffic behaves like a continuous fluid and hence applied the one-directional fluid dynamics equations as summarised below.

$$\frac{du}{dt} = -\frac{c^2}{k}\frac{\partial k}{\partial x} \tag{7.1}$$

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{7.2}$$

Where u is fluid velocity, k is traffic density, x is distance along a passage, t is time, c is constant parameter that is determined from the state of the fluid and q is the vehicle traffic flow in the conservation of flow equation. Since $u = u(x,t)$ and $q = ku$ hence equation 7.1 and equation 7.2 respectively become:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{c^2}{k}\frac{\partial k}{\partial x} = 0 \tag{7.3}$$

$$\frac{\partial k}{\partial t} + u\frac{\partial k}{\partial x} + k\frac{\partial u}{\partial x} = 0 \tag{7.4}$$

Making the presumption that velocity can be considered as a function of density alone $u = u(k)$ the authors then derive:

$$\frac{\partial u}{\partial t} = \frac{du}{dk}\frac{\partial k}{\partial t} \tag{7.5}$$

$$\frac{\partial u}{\partial x} = \frac{du}{dk}\frac{\partial k}{\partial x} \tag{7.6}$$

Then by substituting the above equations 7.5 and 7.6 into 7.3 and 7.4 the following is derived

$$\frac{\partial k}{\partial t} + \left[u + \frac{c^2}{u'k}\right]\frac{\partial k}{\partial x} = 0 \tag{7.7}$$

$$\frac{\partial k}{\partial t} + \left[u + ku'\right]\frac{\partial k}{\partial x} = 4 \tag{7.8}$$

Where $u' = du/dk$. By equating the above equations to 0 they can be solved to yield the density dependence of the traffic velocity as expressed in:

$$u = c\ln\left(k_j/k\right) \tag{7.9}$$

Where c is a constant and k_j is the density at which a traffic jam would occur meaning $u = 0$. In order to find the flow q in terms of density k one can substitute for u in equation 7.9 with $q = uk$ to obtain equation 7.10 below:

$$q = ck \ln \left(k_j / k\right) \tag{7.10}$$

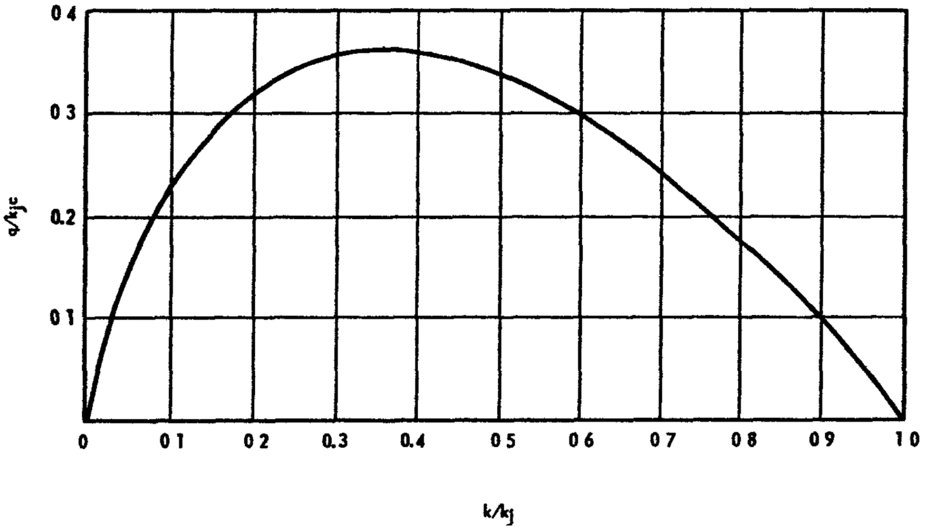


FIGURE 7.1: Normalised traffic flow versus density [83].

This can be represented as shown in Figure 7.1. Here, it can be observed that a certain traffic density the velocity would drop below the optimum value, this is referred to as the critical density. Hence, the *critical density* of an airway in our model would be defined as the density at which capacity (maximum flow) occurs for that given airway. Furthermore, the density at which congestion stops all movement is hence referred to as the *jam density*. These key concepts would be used throughout the proposed model.

7.3 Traffic Optimisation and Deconfliction

In all the vast array of promising UAV applications presented in Chapter 3 section 3.4, in order for UAVs to perform their tasks, efficient and collision-free path planning is a necessity. This section first presents the related work in autonomous mobile robot path planning, followed by a discussion on Pareto optimality and multi-criteria decision making.

7.3.1 Autonomous UAV Path Planning

Path planning for autonomous robotic applications is a research topic that has been actively studied over many years. However, literature have mainly focused on 2-dimensional (2D) and 2.5-dimensional (2.5D) methods [318], while approaches for UAVs, underwater vehicles and other highly mobile autonomous robots requiring 3D path planning, remain less explored. As autonomous mobile robot path planning is proven to be NP-hard, 3D path planning is also NP-hard with an additional dimension, altitude [318].

Furthermore, commonly used UAVs can be categorised as non-holonomic mobile robots [261] as the degree of their controllable actuators is less than their degree of freedom in the space which they operate; therefore, path planning optimisation adds further complexity in comparison to holonomic systems. In order to address such challenges, researchers divide path planning into two main subsystems; a global path planning subsystem complemented by a lower level addressing collision avoidance. While the latter is out of the scope of this work, we address deconfliction simultaneously with path optimisation as will be further explained in Section 7.4. However, the interested reader can find various approaches and algorithms in [79, 250].

With focus on global path planning of UAVs, [317] provide a thorough survey of successful UAV 3D path planning algorithms found in literature. Additionally, the authors analyse and categorise the algorithms into sampling-based, mathematical model based, node-based and bio-inspired algorithms; out of which, we pay particular attention to the latter two, provided our proposed model of Class G. In addition to the well–known Dijkstra and A* algorithms in [176] the authors propose an anytime heuristic search algorithm that improves on classical A* by ensuring that a robot has at least a sub-optimal path at any given time. The authors then develop further on this and propose [177], a heuristic-based re-planning method (AD*) relying on an anytime dynamic A* algorithm to continuously improve its solution within a predefined time frame as well as allow for re-computation of the path when information is updated. Another approach is the Lazy Theta*, proposed in [215], building on the Theta* algorithm, this search method is not constrained to the topology of first hop neighbours in a multilayer network, in turn offers an improvement to classical A*. While the aforementioned algorithms can find optimal paths through decomposing networks, they typically optimise the path efficiency for one objective which makes them not ideal for many UAV applications in complex environments [140].

7.3.2 Pareto-based Techniques

To address this, research turns to multiobjective optimisation approaches which call for solutions that account for multiple cost criteria, where optimising one criterion may be at the cost of another. The complexity of such problems significantly increases with the number of objectives to be optimised, hence making them a challenging research topic. Such problems have been addressed in literature for decades [290]. Broadly, multiobjective optimisation approaches can be classified under four main categories namely, scalar approaches, criterion-based approaches, indicator-based approaches and dominance-based approaches [290].

Scalar approaches could be considered the less complex alternative and are generally accomplished by transforming the different objectives into a single objective function [290], for example, through aggregation methods that compute the weighted sum of utility functions. However, these methods require good knowledge of the problem as the selection of criteria weights is not trivial and small perturbations in the weights can lead to very different solutions. Literature provides multiple application scenarios for such methods. In [271] the authors provide a bi-objective optimisation application scenario of an autonomous underwater vehicle using a weighted sum approach. Additionally, a thorough survey is presented in [145], where the authors, provide an analysis, characterisations and comparison of six common methods of scalarisation in multiobjective optimisation approaches. The properties of the presented methods are investigated with respect to the basic characteristics such as ordering cone, convexity and boundedness, the ability of generating proper efficient solutions, in addition to others. On the contrary, in criterion-based approaches the search is performed by addressing the various non commensurable objectives separately [290].

However, what interest us most are dominance-based and indicator-based optimisation approaches. While dominance-based approaches rely on the concept of dominance and Pareto optimality to guide the search process; the latter rely on quality indicators to drive the search towards the Pareto front eliminating the need for diversity maintenance as it is implicitly taken into account in the performance indicator definition [290]. Such methods have been investigated in the literature for decades with predominant examples of bio-inspired search paradigms like the non-dominated sorting genetic algorithm (NSGA) [278] and variations of NSGA-II [47] and NSGA-III [46] for different environmental models, robot types and applications. On the down side, the main drawback of using evolutionary algorithms for path planning is computational complexity making them more fit for offline centralised approaches than distributed online path planning in autonomous mobile robots and specifically UAVs.

7.3.3 Multi Criteria Decision Making (MCDM)

While obtaining an entire set of non-dominated solutions can present the *decision maker*, whether human user or centralised system, a clear picture of the trade-off relationships among the conflicting objective functions, it could be cumbersome and possible unsuitable for autonomous mobile robot applications. Autonomous robots ultimately will have to be capable of making such selection or decision without or with minimal human intervention, specially in time-critical missions. One approach of addressing such problems is by using Multi Criteria Decision Making (MCDM).

According to Ramesh and Zionts in [243], Multi Criteria Decision Making (MCDM) refers to making decisions in the presence of multiple, usually conflicting, objectives. MCDM methods aid in choosing the more suitable alternatives by analysing the different scope and weights, representing the importance, of given criteria. Broadly, based on the explanation in [293], any decision-making technique involving numerical analysis of alternatives is achieved over three main steps: i) firstly, determining the relevant criteria and alternatives, ii) secondly, attaching numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria, and iii) finally, processing the numerical values to determine a ranking of each alternative. The popularisation of MCDM, over the past years, has led to the proposal of multiple analysis techniques in literature. Some commonly used methods include Weighted Sum Method (WSM), Weighted Product Method (WPM) Analytic Hierarchy Process (AHP) and multiple variations of it, in addition to others like ELECTRE and the TOPSIS methods.

The Weighted Sum Model (WSM) is one of the simplest and earliest methods proposed in literature, however one critical limitation of WSM is that all criteria have to be expressed in exactly the same units. This led to the proposal of the Weighted Product Model (WPM) which is almost identical to WSM with the exception of using multiplication instead of summation, making it a dimensionless method. On the other hand, the Analytic Hierarchy Process (AHP), proposed by Saaty [258], is a later development that has gained a lot of attention over the years compared to WSM and WPM. Literature provides a multitude of variations and revisions to AHP including the revised Analytic Hierarchy Process (rAHP) [23] which is more consistent than the original approach, the Analytic Network Process (ANP) and the Cognitive Hierarchy process (CHP) which are compared in [206].

Literature additionally offers a wide array of applications from energy management [163], supply chain and logistics [65, 310] to many others. However, what interests us most are those related to path planning. In [15] Ayala et al. propose an interactive path planner for pedestrians that adapts to the individual's preferences by incorporating an interactive multi criteria decision approach. Another interesting application is presented in [88]. The paper proposes a multi criteria heuristic algorithm for personalised path planning using AHP. A similar approach is applied to a product distribution path selection in [247]. In [150] the authors propose a two-layer decision approach that integrates the preferences of a flight operator through a multi criteria decision aiding model for UAVs. Some other methods in literature include ELECTRE and the TOPSIS methods, however they are not as widely adopted in scientific community as AHP based techniques, they are gaining interest mainly due to the rational and mathematical approach followed in contrast to the priority weighing in AHP. The interested reader can find a thorough comparison and analysis of the above methods in [293].

However, most of the applications in literature either rely on interactive human decision or present a mobile robot with a set of fixed priorities or weights of the criteria. In contrast, we incorporate an interactive, dynamic multi criteria decision making approach, to the proposed heuristic, allowing every robot to autonomously assess its current status and traffic condition and adjust the criteria weights accordingly, which to the best of our knowledge, has not yet been proposed in the autonomous mobile robot path planning literature.

7.4 Proposed Traffic Optimisation and Deconfliction Model

In the context of UAV dynamic online path planning, the majority of aforementioned solutions presented in literature either address a single optimisation objective or the multiobjective optimisation problem with centralised approaches. Such approaches will eventually face the inherent limitations of centralised systems. To this end, the following subsections present our proposed novel path planning optimisation and deconfliction approach for autonomous UAVs.

7.4.1 Formal Optimisation Model

In alignment with the Class G airspace model presented in Chapter 5 and the illustrative example presented in Section 5.4, this subsection presents the corresponding formulation of the bi-objective optimisation problem of minimising the total travel time and energy consumption of UAV traffic in the network. Based on our weighted multilayer network description [252], the bi-objective function F we aim to optimise can be expressed as:

$$\min \ F = (f_1, f_2) \tag{7.11}$$

$$f_1 = T = \sum_{i=1}^{I} \sum_{l=1}^{L} a_{il} * t_l \tag{7.12}$$

$$f_2 = E = \sum_{i=1}^{I} \sum_{l=1}^{L} a_{il} * e_l \tag{7.13}$$

$$\text{s.t. } \sum_{i=1}^{I} a_{il} = c_l, \ l = 1, \ldots, L, \tag{7.14}$$

$$c_l \leq c_l^{max}, \ l = 1, \ldots, L, \tag{7.15}$$

$$a_{il} \in \{0, 1\}, \ i = 1, \ldots, I, \ l = 1, \ldots, L, \tag{7.16}$$

$$E, T \in \mathbb{N}, \tag{7.17}$$

$$e_l, t_l, c_l \in \mathbb{N}, \ l = 1, \ldots, L, \tag{7.18}$$

where:

F – bi-objective function (f_1, f_2),

T – objective function (time elapsed),

E – objective function (energy consumed),

I – number of UAVs,

i – index for UAVs,

L – number of airways,

l – index for airways,

a – selection indicator for airways / UAVs ($\in 0, 1$),

e – energy consumption component for airways,

t – time elapse component for airways,

c – traffic capacity for airways,

c^{max} – maximum traffic capacity for airways.

In the proposed model, each airway in a path has a critical traffic capacity of UAVs that it can traverse as explained in Section 7.2; in addition to an allowable maximum velocity which is expressed in its simplest form in terms of time t and energy e. Therefore, for a number of UAVs I over a complete path our first utility function (1) addresses our first objective, minimising the total energy consumption while (2) addresses our second objective which is minimising the total travel time. Complementing this approach, is the deconfliction process.

Conflict management is the process of ensuring that UAVs do not collide, we achieve this by following a *strategic* then *tactical* approach (c.f. Table 7.1). The process is divided into three levels where the aim of each is to reduce the need to apply the proceeding level. Starting with strategic traffic density management in the mission planning phase, signified in *equation 7.15*, following through with the dynamic tactical level of maintaining separation and finally evasive manoeuvres.

Similarly, the proposed solution model follows the same three level modus operandi. The novel optimisation approach incorporates an initial global path planner complemented by a dynamic online multiobjective path planner that responds to the traffic changes in the environment and freeing the lower level to worst–case evasive manoeuvres. Table 7.2 outlines the proposed multi-level solution approach emphasising the key differences between the three levels and highlighting the novel intermediate dynamic online path planning level.
To this end, in contrast with the majority of heuristics in literature, the solution approach we devise does not only focus on optimising distance and time but optimise travel time while taking into consideration energy limitations, inspired by energy-aware routing in wireless sensors networks [314]. Therefore, inspired by the work presented in [48] on Inverted Ant Colony Optimisation (IACO) for vehicle traffic management we rely on our work in [44] to adopt a pheromone guided heuristic in order to evaluate UAV traffic behaviour on airways within Class G airspace. The following sections of the chapter detail the devised heuristics in a incremental order with regard to complexity. Stage I presents the approaches used in the corresponding first stage of experimentation with the aim of assessing the performance of a completely distributed traffic management system in comparison to a centralised one. While Stage II extend on the latter to consider multiple optimisation objectives and rely on dynamic decision making approaches to allow UAVs to autonomously select a solution based on their current status and local knowledge.

7.4.2 Stage I

This section introduces three heuristics used in our our first stage of experiments in Chapter 8. The first heuristic is a static path planning approach resembling a centralised predefined path generator; the second is a probabilistic heuristic addressing the dynamic nature of our proposed model, however, assuming global knowledge of the traffic conditions in the network, this resembles vehicle navigation rerouting systems such as Google Maps; while the third is a pheromone guided greedy heuristic relying on local knowledge of traffic conditions. At Stage I, the proposed heuristics are used a simplified test-bed for the multiobjective Stage II, optimising a single objective either time or energy.

Figure 7.2 illustrates a simplified flowchart of the proposed approaches of Stage I.

Global Offline Static—UTM (GOS)

To address the static nature of the network, at the beginning, UAVs follow a pre-computed shortest path from origin to destination. This shortest path is calculated with the A* algorithm [96] using a the respective network weights t or e, depending on the minimisation objective of each UAV and a heuristic that takes into account the Euclidean distance between network nodes, assuming optimal traffic conditions,

Conflict Management	
Strategic	I. Mission Planning - Traffic density management
Tactical	II. Remaining Clear - Maintaining separation III. Collision Avoidance - Evasive manoeuvres

TABLE 7.1: Different deconfliction levels.

	Strategic	**Tactical**	
	High Level	**Novel Intermediate Level**	**Lower Level**
Knowledge	Global	Local	Local
Planning	Offline	Online	Online
Nature	Static	Dynamic	Dynamic
Computation	High	Medium	Low
Time	High	Medium	Low
Approach	Proactive	Responsive	Reactive
Usage	Initial global planner	Respond to dynamic conditions	React to abrupt situations

TABLE 7.2: Multi-level solution approach.

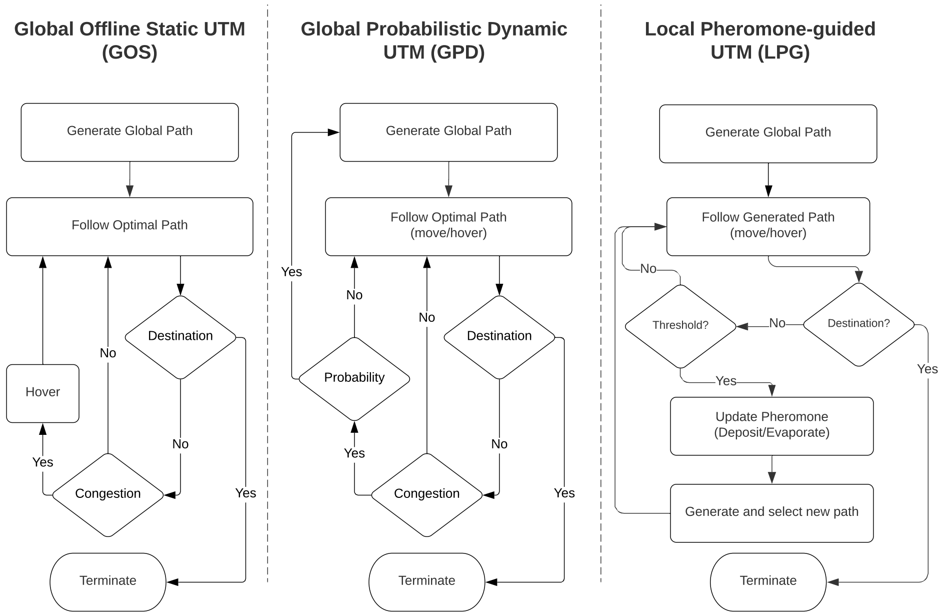


FIGURE 7.2: Simplified flowchart - stage I approaches.

Heuristic 1 : Global Offline Static – UTM (GOS)

```
Data: network, weights $(t, e, c)$, start, destination, A*_shortest_path
1 while UAV not at destination do
2     take next_move from A*_shortest_path
      if $c_l < c_l^{max}$ then
3         set current to next_move                          ▷ UAV move
          update $t_l, e_l, c_l$
4     else
5         add to queue on node                              ▷ hover
6     end
7 end
```

no congestion and that UAVs can traverse the network at the maximum allowable speed of the layer. UAVs follow their given path (*A*_shortest_path*) and update the weights t, e, c of the respective airway l as long as the traffic capacity on the airway, $c_l < c_l^{max}$ (c.f. lines *1–4* in Heuristic 1). Once maximum capacity is reached, UAVs queue at the airway entrance node, until the condition $c_l < c_l^{max}$ is satisfied (c.f. line *5* in Heuristic 1).

Global Probabilistic Dynamic—UTM (GPD)

Assuming global knowledge of network weights, firstly, UAVs follow the shortest path initially computed by A* algorithm (c.f. lines *8–11* in Heuristic 2); however, on the contrary to GOS, when they encounter congestion on one airway, that is, when the maximum capacity of this airway is reached: $c_l = c_l^{max}$, each UAV takes a probabilistic decision $p_{reroute}$ of either hovering in queue at the current node or to take an alternative shortest path computed with the same A* algorithm as in GOS on the multilayer network with updated t, e, c weights (c.f. lines *12–16* in Heuristic 2).

Heuristic 2 : Global Probabilistic Dynamic—UTM (GPD)

```
Data: network, weights ($t, e, c$), start, destination, A*_shortest_path
8  while UAV not at destination do
9      take next_move from A*_shortest_path
       if $c_l < c_l^{max}$ then
10         set current to next_move                                        ▷ UAV move
           update $t_l, e_l, c_l$
11     else
12         if $rand < p_{reroute}$ then
13             compute new A*_shortest_path from current to destination    ▷ using A*
14         else
15             add to queue on node                                        ▷ hover
16         end
17     end
18 end
```

Local Pheromone Guided – UTM (LPG)

In contrast to the aforementioned heuristics of GOS and GPD, the Local Pheromone Guided (LPG) UAV traffic management approach allows for a distributed traffic behaviour where UAVs rely on local knowledge of traffic condition as explained in Heuristic 3 below.

In LPG, UAVs start by following the offline generated shortest path (*A*_shortest_path*) similar to in GOS and GPD, until the traffic on the next airway is superior to a predefined threshold defined by T_{lim}, that is, when $c_l = T_{lim}$ where $T_{lim} < c_l^{max}$ (c.f. lines *19–22* in Heuristic 3). In reality, T_{lim} would correspond to the critical traffic density explained in traffic theory as the capacity after which traffic flow becomes congested as detailed in Section 7.2. At that stage each UAV lays down a pheromone trail τ, where $\tau_l = 1/c_l^{max}$ of airway l. The deposited trail of pheromone acts as a repellent to other UAVs, hence making the airway less desirable to take. In our model, intersecting nodes act as decision points at which the following UAVs receive the updated pheromone level and use the commonly used state transition rule introduced in [51] to decide which airway to select. This can be expressed as a function of the pheromone on the airway in addition to the quality of the airway: $p_l^i = f(\tau_l, \eta_l)$, where p_l^i is the probabilistic transition rule for UAV i to take airway l with quality η_l represented by t/c_l^{max} or e/c_l^{max} depending on the optimisation objective of the UAV. UAVs then take a decision of either staying on the same path or selecting a new airway. If the latter, UAVs recompute a path to destination, from the newly selected airway, using A* on the multilayer network with initial weights, assuming optimal

Heuristic 3 : Local Pheromone Guided – UTM (LPG)

```
Data: network, weights $(t, e, c)$, start, destination, traffic_threshold ($T_{lim}$), A*_shortest_path
19 while UAV not at destination do
20     take next_move from A*_shortest_path
       if $c_l \leq T_{lim}$ then
21         set current to next_move                                          ▷ UAV move
           update $t_l, e_l, c_l$
22     else
23         evaluate alternative airway quality
           if $rand < p_{reroute}$ then
24             set current to next_move                                      ▷ UAV move
               compute new A*_shortest_path from current to destination      ▷ using A*
               update $t_l, e_l, c_l$
               update pheromone $\tau$
25         else
26             if $c_l < c_l^{max}$ then
27                 set current to next_move                                  ▷ UAV move
                   update $t_l, e_l, c_l$
                   update pheromone $\tau$
28             else
29                 add to queue on node                                      ▷ hover
30             end
31         end
32     end
33 end
```

traffic conditions (c.f. lines *23–25* in Heuristic 3), otherwise UAVs remain on their initial path (c.f. lines *26–30* in Heuristic 3).

7.4.3 Stage II

This section introduces the heuristics used in our our second stage of experiments in Chapter 8. Building on the first stage of heuristic, here we extend the Local Pheromone Guided (LPG) A* heuristic presented in [253] allowing individual UAVs to compute a non-dominated set of paths at every individual search step, i.e. when facing traffic congestion, and rely on simple dynamically updated multi-criteria decision matrix to select a solution autonomously.
Figure 7.3 illustrates a simplified flowchart of the proposed algorithm divided into a higher proactive layer, a responsive dynamic intermediate layer and a reactive lower layer following a strategic then tactical 3 level approach as explained in Section 7.4.

The extended Local Pheromone Guided (eLPG) UAV traffic management extends LPG to a multiobjective distributed path planning approach inspired by the multi-objective A* (MO_A*) search algorithm proposed in [186] and detailed in [187]. The algorithm is effectively the classical search algorithm with the key modification of computing the Pareto front of the cost criteria instead of summing them, hence the name *Pareto_A**. The following subsection details the approach used.

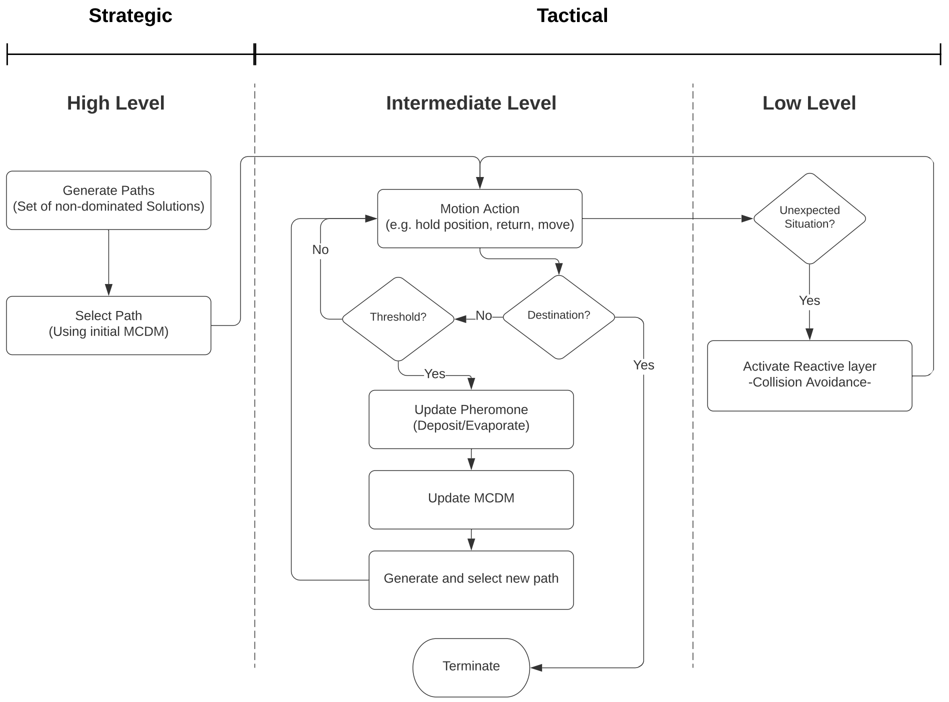


FIGURE 7.3: Simplified flowchart - stage II approach.

Extended Local Pheromone Guided – UTM (eLPG)

Heuristic 4 : Extended Local Pheromone Guided – UTM (eLPG)

Data: network, weights (t, e, c), start, destination (dest), traffic_threshold (T_{lim}), criteria_matrix

```
while UAV not at dest do
    compute set of solution_paths                        ▷ using Pareto_A*
    select best_path                                     ▷ using criteria_matrix
    take next_move from best_path
    if $c_l \leq T_{lim}$ then
        set current to next_move                         ▷ UAV move
        update $t_l, e_l, c_l$
    else
        compute solution_paths to dest                   ▷ using Pareto_A*
        check/update criteria_matrix                     ▷ TOPSIS
        select best_path                                 ▷ using criteria_matrix
        set current to next_move                         ▷ UAV move
        update $t_l, e_l, c_l$
        update pheromone $\tau$
    end
end
```

The eLPG presented in Heuristic 4, allows UAVs with knowledge of only their origin and destination to generate a set of solutions/paths using *Pareto_A** then relying on their multi-criteria decision matrix, each UAV selects one of the generated paths to follow. UAVs start following the selected shortest path until the traffic on the next airway is superior to a predefined threshold defined by T_{lim}, that is, when $c_l = T_{lim}$ where $T_{lim} < c_l^{max}$ (cf. lines *1–4* in Heuristic 1). In reality, T_{lim} would correspond to the critical traffic density explained in traffic theory as the capacity after which traffic flow becomes congested. At that stage each UAV lays down a pheromone trail τ, where $\tau_l = 1/c_l^{max}$ of airway l. The deposited trail of pheromone acts as a repellent to other UAVs, hence making the airway less desirable to take. In the devised model, intersecting nodes act as decision points at which the following UAVs receive the updated pheromone level and use it to estimate an update of corresponding airways' weights in order to locally compute new alternative paths to their destination (cf. lines *4–6* in Heuristic 4).

At this stage, we explore three different multiobjective A* implementation approaches based on two proposals from scientific literature found in [171, 280]. Additionally for the decision making aspect when two or more solutions exist, UAVs rely on a dynamic TOPSIS to make their selection between the generated set of solution from the Pareto-based approach. While the approach applied is the similar to the classical TOPSIS, it considers the *criteria* and *alternatives* as temporary variables instead of and therefore provides autonomous UAVs a logical framework to determine the cost of each alternative at a given step. In other words, as UAVs traverse the network, alternatives present the different solutions/paths at every decision step where the criteria at that step vary with the state of each UAV. As an initial stage, we consider the energy criterion weight to vary with the level of consumption as guided by $c_i^p = c_0^p \cdot e^{k \cdot p_i}$ where c_i^p is the energy criterion weight at step i, c_0^p is the initial weight of the criterion, k a growth constant and p_i represents the battery consumption level. Hence, the more energy UAVs consume the greater the impact of energy conservation would be on their decision between alternatives.

7.5 Summary

To this end, Chapter 7 presented, in the above sections, a review of state of the art path planning approaches as well as a discussion on Pareto-based techniques and multi-criteria decision making methods. The chapter then extended a novel path planning optimisation and collision avoidance approach, a formal model corresponding to the Class G airspace model and information model presented in Chapters 5 and 6 followed by a set of heuristics. The devised approaches, presented over Stage I and II, followed a three level approach with an initial global planner, a novel intermediate dynamic level to respond to the changing traffic conditions complemented by a lower reactive collision avoidance level.

Chapter 8 hence, builds on the work presented here devise a set of experimental simulations to test and compare the traffic performance when using the difference heuristics.

End of Chapter 7

Chapter 8

Simulations and Results

8.1 Introduction

Chapters 5, 6 and 7 detailed our proposed UAV Traffic Management system framework in terms of the airspace structure, the communication and information exchange model and the traffic optimisation approaches. In order to build and safely operate autonomous systems of robots whether on ground or in air, rigorous testing and certification is required. However, such real world experimentation come at a high cost due to the high risk involved specially at the early stages of development. To this end, simulation environments offer a more cost-effective alternative to early stage real-world experiments. Additionally, simulations offer lower-risk testing where simulated environments are controllable and allow reproducability of research as well as simpler troubleshooting of misbehaving algorithms.

The main goal of this chapter is therefore to explain the simulation approach and discuss the results of the proposed UAV Traffic Management algorithms. The chapter is structured as follows, Section 8.2 presents an overview of the evaluation metrics and simulation stages. Section 8.3 covers the validation and verification of the simulation model as well as the first stage of experiments followed by the second stage of experiments in Section 8.4. Finally Section 8.5 concludes the chapter by elaborating on the findings, the delimitation of the work and simulation assumptions.

8.2 Simulation and Evaluation Approaches

In order to evaluate the traffic optimisation approaches detailed in Chapter 7, this section gives an overview of the evaluation criteria and the selected indices as well as outlines the methodology followed throughout the different stages of experimentation.

8.2.1 Evaluation Metrics and Traffic Performance Indicators

A *metric* is a standard definition of any measurable quantity. Given the nature of UAV operations and their high level of mobility, evaluation metrics and traffic performance indices for this research work are of critical importance. Suitable metrics and indices can be said to be standard measurable quantities that indicate some aspect of performance of the said system, they should exhibit certain characteristics to be valuable and practical. Hence the selected evaluation metrics and performance indices should:

- Be quantifiable or able to be determined from other measurements.
- Have a clear definition, including boundaries of the measurements.
- Indicate progress toward a performance area.
- Answer specific questions related to the evaluation of results and the performance of a system.

Moreover, they should be consistent with the performance objective and performance targets of the system. They should be compatible with existing and future UTM systems as well as meet the expectations of the set goals and be able to measure and track progress toward the Key Performance Area (KPA).

For a distributed UTM system several key performance indicators (KPIs) have been proposed in order to achieve the system's set goals. As performance management is relevant to the success of the future ATM system policy makers, designers, Airport officials, Airlines operators, ANSPs, researchers and other stakeholders shall rely extensively on metrics for assessment. Considering the structure and size of future UTM systems, the task of defining or choosing metrics might prove to be complex. One form of confusion or complexity is that as there are no defined general or standardised methods for data processing, further contributing to the complexity of data comparison or compilation.

However, since future UTM should allow the integration with existing ATM systems, they in turn should rely on comparable indices and metrics in accordance with the performance management frameworks of EU's SESAR and USA's NextGen [38, 62, 289] and should cover items such as *capacity, cost-effectiveness, efficiency, flexibility, predictability, safety, security, communication availability and environmental impact*.

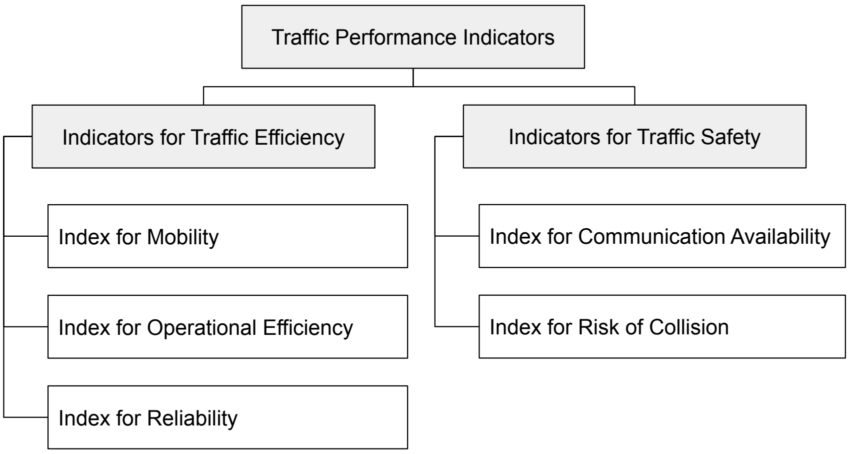


FIGURE 8.1: Selected traffic performance indicators.

Selected Traffic Performance Indices

To this end we divide the performance indices into the following two sub-classes (c.f. Figure 8.1):

- **Indices for traffic efficiency**. The term traffic efficiency may cover a variety of aspects, however, for the purposes of this work we consider, based on the taxonomy in [144], that traffic efficiency is constituted by the following sub-categories:
  - Index for mobility – mainly concerned with the travel time in the network of airways.
  - Index for operational efficiency – operational efficiency refers to the good organisation of resources that facilitate or enable an acceptable level of transport output [144] and correlates to traffic energy and is, as such, an important constituent of traffic efficiency.
  - Index for reliability – reliability is another important function of air transport systems, which expresses the ease of mobility. Since reliability is concerned with travel time variability, airspace usage and operational efficiency, reliability could be quantified by studying congestion patterns or total/average speed [144].
- **Indices for safety**. The safety level of any traffic system or transport infrastructure can be defined by the number and impact of accidents. Safety measures can therefore be seen as either infrastructure-related or UAV-related. Indices of traffic safety can therefore constituted by the following sub-categories:
  - Index for communication availability – information exchange systems are the backbone of tactical level airspace management (c.f. Chapter 6). Communication availability can hence be linked to traffic safety indices. From direct warning of dangerous situations and conflicts to UAVs and UAV operators, to supplementary flight information. However, such systems are still the subject of research and development and therefore not yet available as wide-area applications, the calculation of an index for their safety impact is therefore not trivial and only limited to theoretical means.
  - Index for risk of collision – collision rate, number of fatalities/injured and economical damage are the most commonly-used performance indicators of traffic safety. However, similar to communication availability, indicators for UTM are still subject of research and development and therefore out of scope of this work. For reference we use SORA [29] for other models, the interested reader can refer to [248, 299].

To this end, in order to comply with the objectives outlined in the optimisation model proposed in Chapter 7 to address UAV traffic management in a fully distributed UTM, we select the following as the two main performance indicators:

- ***UAVs' total energy*** – as an index for operational efficiency measured by energy required/consumed by UAVs to reach their destination.
- ***UAVs' total time*** – as an index for mobility measured by the time taken for UAVs to reach their destination.

Additionally, we assess the reliability of the traffic management system by studying the patterns of flight speeds, congestion and modes of flight. It is additionally worth noting that at this stage of work we do not consider communication availability and risk of collisions as explained in subsection 8.2.3.

Selected Evaluation Metrics

Besides the traffic performance indices explained above - which would be the main quality metrics used in the first stage of simulations as explained in 8.2.2, for the multiobjective simulations results we additionally rely on standardised metrics to evaluate the quality of the Pareto front approximations obtained by the algorithms used. The work in [14] presents and reviews 57 metrics used to evaluate quality of results of multiobjective optimisation approaches. The work partitions the proposed metrics into four groups according to their properties, namely:

- *cardinality*: to quantify the number of non-dominated points generated by an algorithm;
- *convergence*: to quantify how close a set of non-dominated points is from the Pareto front in the objective space;
- *distribution and spread*: classified into two sub-groups - one to quantify how well distributed the points are on the Pareto front approximation; the second to evaluate the Pareto front in terms of extreme points of the Pareto front;
- *convergence and distribution*: metrics that quantify both the properties of convergence and distribution.

Each of the evaluation metrics quantifies a different aspect of the front and hence, relying solely on one could induce wrong conclusions. In this work, for the evaluation of the multiobjective approaches presented in the second stage of simulations 8.2.2, we study the convergence, distribution & spread and convergence & distribution of the obtained fronts. To this end we study the *Inverted Generational Distance* (IGD), *Spread* (Δ), and *Hypervolume* (HV), which account for accuracy of solutions, diversity, and both of them simultaneously as explained in [265].

- *Inverted Generational Distance* (IGD): proposed in [37], IGD measures the average euclidean distance from the found solutions to the Pareto front and can be expressed as:

  $$IGD = \frac{1}{|P^*|} \sum_{v \in P*} d(v, P) \tag{8.1}$$

  where P^* is the Pareto front approximation provided by the algorithm, P is the reference Pareto front, and $d(v, P)$ is the Euclidean distance from point v on the Pareto front approximation found to the closest one in the reference front. Fronts with small IGD values are more desirable. Equation 8.1 results in value 0 if all solutions generated by the algorithm are on the front.

- *Spread* (Δ): proposed in[309] as an improvement on the *spacing* metric initially presented in [266], it quantifies the diversity of solutions in the front by means of their spread along the front and can be expressed as:

  $$\Delta = \frac{d_f + d_l + \sum_{i=1}^{N-1} |d_i - \bar{d}|}{d_f + d_l + (N-1)\bar{d}} \tag{8.2}$$

where d_i is the Euclidean distance between consecutive solutions,$\bar{d}$ is the mean of these distances, and d_f and d_l are the Euclidean distances to the extreme solutions of the reference Pareto front in the objective space. Equation 8.2 results in value 0 for an ideal distribution with a perfect spread of the solutions on the front.

- *Hypervolume* (HV): also known as the *S-metric* was first introduced in [333] and it is a metric that evaluates the volume - in the objective space - covered by members of a non-dominated set of solutions Q, for problems where all objectives are to be minimised. As explained in [265], mathematically, for each solution iQ, a hypercube v_i is constructed with a reference point W and the solution i as the diagonal corners of the hypercube. The reference point can simply be found by constructing a vector of worst objective function values. Thereafter, a union of all hypercubes is found and its *hypervolume* (HV) can be expressed as shown in equation 8.3:

$$HV = \text{ volume } \left(\bigcup_{i=1}^{|Q|} v_i \right) \tag{8.3}$$

  Where a higher value of HV indicates a better approximation of the front.

Nevertheless, throughout this work we have also considered the following metrics adopted from [14]:

- *Generational Distance* (GD): can be defined by equation 8.4

$$GD(S,P) = \frac{1}{|S|} \left(\sum_{s \in S} \min_{r \in P} \|F(s) - F(r)\|^p \right)^{\frac{1}{p}} \tag{8.4}$$

  where $|S|$ is the number of points in an Pareto set approximation and P a discrete representation of the Pareto front.

- *Spacing* (SP): this metric can be expressed as:

$$SP(S) = \sqrt{\frac{1}{|S|-1} \sum_{i=1}^{|S|} (\bar{d} - d_i)^2} \tag{8.5}$$

  where $d_i = \min_{(s_i,s_j) \in S, s_i \neq s_j} \left\| F\left(s_i\right) - F\left(s_j\right) \right\|_1$ is the l_1 distance between a point $s_i \in S$ and the closest point of the Pareto front approximation produced by the same algorithm, and $\bar{d}$ the mean of the d_i.

- *Averaged Hausdorff Distance* (Δ_P): to combine IGD and GD into one new indicator expressed as:

$$\Delta_P(S,P) = \max \left\{ GD_p(S,P), \mathrm{IGD}_p(S,P) \right\} \tag{8.6}$$

  where GD_p and IGD_p are slightly modified versions of GD and IGD and can be defined as:

$$GD_p(S,P) = \left(\frac{1}{|S|} \sum_{s \in S} \mathrm{dist}(s,P)^p \right)^{\frac{1}{p}} \quad IGD_p(S,P) = \left(\frac{1}{|P|} \sum_{i=1}^{|P|} \mathrm{dist}(i,S)^p \right)^{\frac{1}{p}} \tag{8.7}$$

$$IGD_p(S,P) = \left(\frac{1}{|P|}\sum_{i=1}^{|P|}\mathrm{dist}(i,S)^p\right)^{\frac{1}{p}} \tag{8.8}$$

8.2.2 Simulation Stages

Experimental simulations were conducted on two stages. The first stage focuses on the validation and verification of the model and parameters. At the initial stage, a single optimisation objective is considered and the performance of the first three proposed algorithms is compared. The latter stage of experimentation extends and builds on the first stage. The second stage introduces more realistic simulation environments and airspace model and tests the performance of traffic when implementing a more complex multiobjective optimisation model. The following sections of this chapter will further elaborate on the experiments parameters and results.

8.2.3 Assumptions and Incentives

This subsection outlines the main assumptions made. We assume, throughout all stages of experimentation, that all UAVs are technically identical multi-rotor UAVs capable of hovering. Although our traffic optimisation approaches simultaneously address UAV collision avoidance and deconfliction, we assume all UAVs are capable of maintaining separation and complying with deconfliction protocols. That being said, our path optimisation approach assumes perfect communication links, with no latency or packet loss, between UAVs at this stage of work. Additionally, wind and other weather parameters such as temperature are assumed to have no effect on energy consumption. Similarly, we assume, acceleration and deceleration have a negligible effect on power consumption.

8.3 Stage I - Model Verification and Validation

The main goal of this first stage of experimentation, is to verify the UTM model design and simulation environment as well as validate the initial results of our optimisation approach then test UAV traffic performance using single objective optimisation. For this purpose, initial simplified instances are selected and later incremented to accommodate larger traffic samples in order to test the performance of the system in extreme traffic congestion conditions. The remainder of this section describes the experimental setup as well as the results obtained.

8.3.1 Experimental Setup

For the first stage, experiments are conducted on a three layer network based on the Erdős – Rényi model using Python's NetworkX library and the multiNetX package. The parameters used for the experiments are described in Table 8.1. Each layer contains the same number of nodes, and each airway (intra and inter network) is assigned three weights, t, e and c, uniformly at random in predefined intervals. Figure 8.2 presents an example of a three layer network with 75 nodes (25 nodes per layer).

Stage I is composed of the 4 main experiments described below:
For all four experiments we compare total UAVs' travel time in the network *in arbitrary time units*, total UAVs' energy consumption *in arbitrary energy units*, as well as

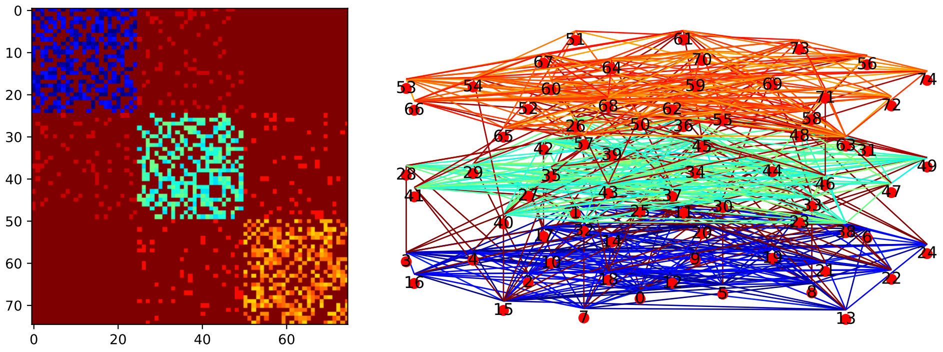


FIGURE 8.2: Example of a 75-Node three layer network and its adjacency matrix.

the number of path changes, network layer change and total UAVs' queuing counts.

- **Experiment 1:** The first experiment aims to validate the UTM model by studying the behaviour of UAV traffic when using the GPD and LPG in comparison to using the centralised approach of GOS.
- **Experiment 2:** The second experiment aims to investigate the effect of varying the decision probability $p_{reroute}$ of GPD on its performance. With all UAVs having the same origin and destination pairs for all 5 traffic samples, the decision probability $p_{reroute}$ is varied between 50%, 80% and 100% (c.f. Table 8.1), firstly with all UAVs having the same minimisation objective (i.e., time) and in a second stage with each UAV assigned either time or energy as objective.
- **Experiment 3:** The third experiment aims to study the effect of varying the traffic threshold T_{lim} of LPG, which in turn varies the point at which UAVs start depositing pheromones on the network airways. Ensuring all UAVs have the same origin and destination pairs for all 5 traffic samples, T_{lim} is varied between 0%, 50% and 80% on traffic samples with mixed minimisation objectives.
- **Experiment 4:** Finally, the main objective of the last experiment is to study the performance of the three heuristics (GOS, GPD, LPG) in a more realistic scenario. Each UAV is given a different pair of origin and destination and a minimisation objective (energy 7.11 or time 7.12). The origin and destination pairs are all on the lowest layer and are more than two hops apart. The network and traffic sample size allow that airways might be shared by UAVs, hence ensuring that congestion can occur. The traffic threshold T_{lim} value of LPG and decision probability $p_{reroute}$ of GPD that demonstrated best performance in the first two experiments are used.

As shown in Table 8.1 a single network with a total of 300 nodes and 3 layers (100 nodes per layer) is used for Stage I. Between every pair of nodes, there is a 20% probability an edge is created. The ranges of the three airway weights (time, energy and capacity) were selected to ensure that the lowest network layer allows less energy consumption by permitting UAVs to fly at their optimum or near optimum lateral velocity – *the velocity at which a UAV is most energy efficient benefiting from transitional lift* as explained in Chapter 5; while the higher layers allow incremental increase in

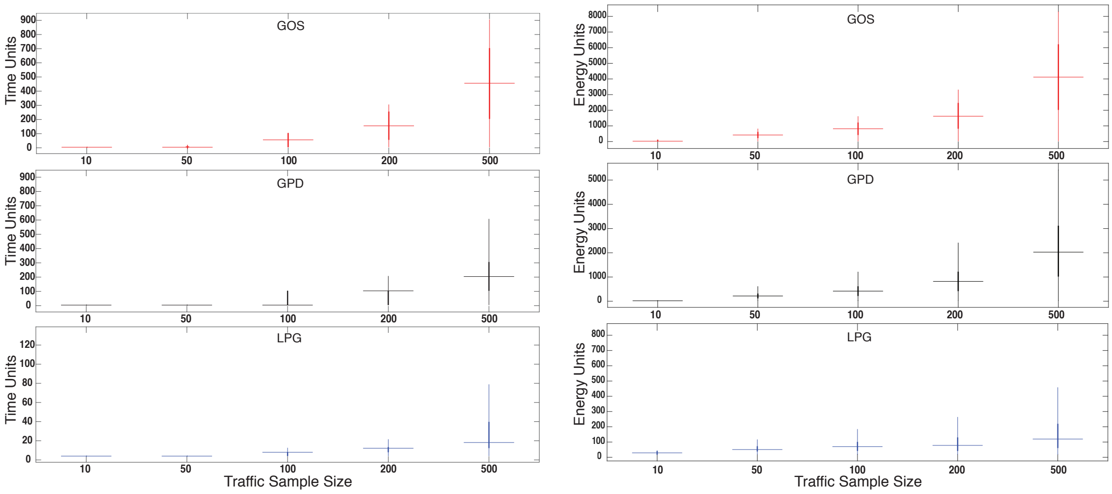
Parameter	**Value**
Number of UAVs (*experiment 1,2 & 3*)	10, 50, 100, 200, 500
Number of UAVs (*experiment 4*)	10, 50, 100, 200, 500, 1000, 1500
Number of nodes	100 per layer
Number of layers	3
Edge creation probability	20%
Interlayer energy weight interval	[15,20]
Intralayer energy weight intervals	[5,10],[15,20],[25,30]
Interlayer time weight interval	[1,5]
Intralayer time weight intervals	[25,30],[15,20],[5,10]
Interlayer capacity weight interval	50
Intralayer capacity weight interval	[1,5]
GPD decision probability ($p_{reroute}$)	50%, 80%, 100%
LPG T_{lim} percentage of c_l^{max}	0%, 50%, 80%

TABLE 8.1: Stage I: experiments parameters.

flight velocity, hence reduce travel time at the cost of more energy consumption. Additionally, UAVs hovering in queuing state consume more energy than those in lateral flight. This is supported by the general power consumption model explained in [113]. The selected capacity ranges also ensure that congestion can occur at different network layers for the tested UAV traffic values. At this initial stage of validation, five traffic sample sizes were generated ranging from 10 to 500 UAVs for the first 3 experiments and from 10 to 1500 for the final experiment. All UAVs are assigned a pair of origin and destination nodes, both located on the lowest layer. All pairs are similar for experiment 1, 2 and 3 while they differ in experiment 4. Each UAV keeps record of its current position, destination as well as its total travel time and energy consumption. Simulations were run 30 times for probabilistic heuristics. Statistical confidence in our comparisons is assessed by performing Kruskal-Wallis test [162] and by performing the Wilcoxon test [308] for Experiment 4.

8.3.2 Results and Analysis

This subsection presents the results of the first stage of experimentation and explores the findings [252, 253]. The impact on the total UAVs' travel time in the network, total UAVs' energy consumption as well as the number of path changes, network layer change and queuing/hovering counts is explored. All obtained results are presented in Figures 8.3–8.7 and summarised in Tables 8.2–8.6. Figures 8.4–8.6 present the impact in traffic performance by indicating the median, 25^{th} and 75^{th} percentile, while Tables 8.3–8.6 present the mean and standard deviation in the results after 30 runs of the probabilistic heuristics for every varied parameter over all traffic samples: for every T_{lim} in LPG and for every $p_{rerouting}$ in GPD. Statistical confidence in our comparisons is assessed by performing Kruskal-Wallis test [162] for Experiments 2 and 3 respectively and by performing the Wilcoxon test [308] for Experiment 4. The overall best result per comparison parameter is shown in bold. Additionally, the dark grey background emphasises the best results that showed statistically significant difference with a 95% confidence.



(a) Total UAVs' travel time

(b) Total UAVs' energy consumption

FIGURE 8.3: Total UAVs' time and energy consumption

Experiment 1: Validation and Comparison of GOS, GPD and LPG

The first experiment aims to validate the UTM model by studying the behaviour of UAV traffic when using the GPD and LPG in comparison to using the centralised approach of GOS.

Results show that the performance changes drastically between GOS in comparison to GPD and LPG. It can be observed that the behaviour caused by UAVs' local decisions leads to a decrease in traffic on widely used airways. This in turn led to improvements in traffic at a local and global level. When comparing results with different sample sizes, greater improvements are seen for larger traffic samples sizes to smaller ones. Comparing the UAVs total travel time of 500 UAVs for all tests in Figure 8.3. shows a 55.26% reduction for GPD and a 93.64% reduction for LPG when compared to GOS. A similar behaviour is observed in the energy plots in Figure 8.3 with a 50.82% reduction in energy consumption for the larger sample for GPD and 97.09% for LPG. This is further supported in Table 8.2 where it is observed that in LPG, UAVs were in queue 93.98% less than in GPD and 97.07% less than in GOS. However, UAVs showed a tendency to change layers 20.81% more in LPG compared to GOS and 17.21% more compared to GPD (c.f. Table 8.2). This indicates that UAVs' local selection of sub-optimal airways to avoid potentially congested paths still led to a global system's improvement through traffic distribution.
The results obtained in the first experiment support the initial hypothesis of this work and offer a first validation to the proposed distributed model of UAV traffic management. The following experiments in Stage I further investigate GPD and LPG behaviour by varying their parameters.

Experiment 2: Impact of $p_{rerouting}$ on GPD Performance

In this second experiment we aim to study the impact of the decision probability $p_{reroute}$ on the performance of GPD, firstly, for traffic samples consisting of UAVs with the same minimisation objective, then with traffic samples with varying minimisation objectives. Three $p_{reroute}$ values are tested as indicated in Table 8.1: 50%, 80% and 100%.

Indices	**Total Value for Traffic Sample Size**				
	10	**50**	**100**	**200**	**500**
GOS					
Queuing	0	0	50	300	2250
Layer Changes	60	300	600	1200	3000
Path Changes	0	0	0	0	0
GPD					
Queuing	0	0	24 ± 25%	152.5 ± 10.16%	1075 ± 4.92%
Layer Changes	60	300	600	1200	3108 ± 0.91%
Path Changes	0	0	26 ± 23.07%	147.52 ± 10.51%	1081.5 ± 3.65%
LPG					
Queuing	0	0	0	24 ± 20.83%	62.5 ± 29.6%
Layer Changes	60	302 ± 0.66%	656 ± 0.31%	1291 ± 0.54%	3619 ± 0.47%
Path Changes	0	1 ± 100%	17 ± 41.2%	135.5 ± 4.8%	576.51 ± 2.69%

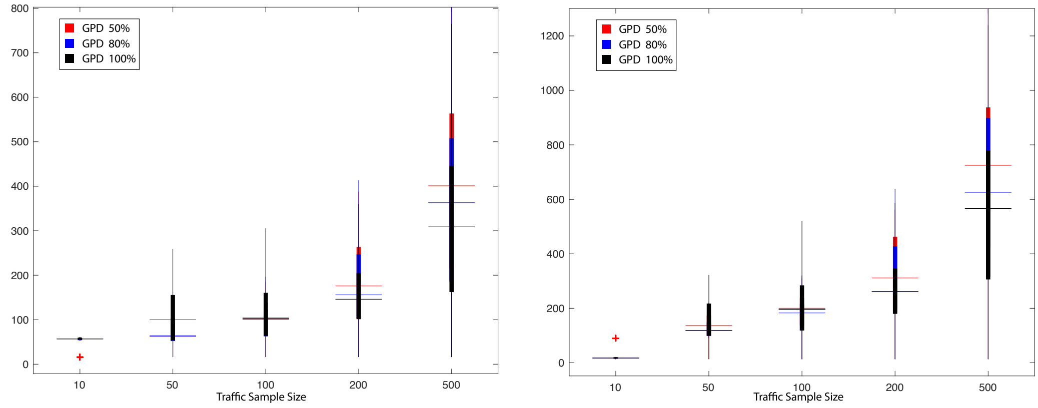
TABLE 8.2: Performance value ranges per sample size.

Traffic	$p_{reroute}$	**Time**		**Energy**		**Path Changes**		**Layer Changes**		**Queue Counts**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
10	50%	**52.9**	**12.562**	**24.3**	**22.073**	1	0	6	0	**0**	**0**
	80%	55.22	13.532	24.913	24.122	0.733	0.442	4.4	2.657	0.267	0.442
	100%	59.57	14.195	26.063	27.518	**0.233**	**0.423**	**1.4**	2.541	0.767	0.423
50	50%	72.58	32.991	126.06	60.396	41	0	246	0	**0**	**0**
	80%	**71.609**	**31.663**	**113.490**	**52.779**	31.1	1.578	180.533	12.631	14.067	4.7127
	100%	95.709	54.985	142.730	85.650	**19.4**	**2.260**	**108.6**	**13.237**	46.767	6.683
100	50%	101.54	44.173	185.78	77.196	91	0	546	0	**41**	**0**
	80%	**97.807**	**41.408**	**168.034**	**71.125**	80.667	3.123	444.8	11.975	53.067	1.999
	100%	119.549	68.633	203.498	112.434	**55.533**	**2.391**	**311.4**	**14.881**	132.4	13.439
200	50%	184.77	98.680	321.89	152.576	323	0	1146	0	273	0
	80%	174.292	98.3507	293.762	153.836	241.2	4.942	1012.2	9.789	**255.767**	**2.362**
	100%	**155.051**	**79.231**	**274.623**	**138.601**	**142.333**	**3.261**	**790.667**	15.086	344.7	15.775
500	50%	403.158	218.089	692.006	359.752	2219	0	2946	0	2169	0
	80%	362.4707	200.818	626.507	340.444	1474.867	20.884	2746	8.884	2002.067	9.609
	100%	**317.376**	175.792	**560.534**	297.477	**660.667**	23.310	**2403.533**	23.408	**1932.6**	5.897

TABLE 8.3: Impact on traffic performance from varying $p_{reroute}$ in Global Probabilistic Dynamic (GPD) (50%, 80%, 100%).

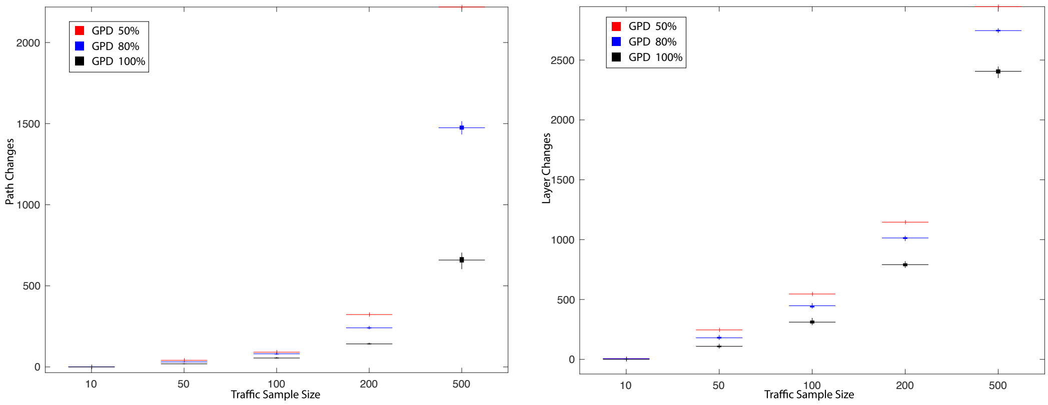
It can be deduced from Table 8.3 and Figure 8.4, of the first part of the experiment, that for the smaller traffic sample sizes of 10 and 50, GPD with $p_{reroute}$ 50% and 80% generally showed improvement over $p_{reroute}$ of 100% in total UAVs' travel time and energy consumption. Nevertheless, $p_{reroute}$ of 100% showed better performance when it came to total traffic path and layer changes for the same samples. However, since the main global objective is a scalable system, it is important to study the performance of the heuristic at larger sample sizes. While that is the case, GPD with $p_{reroute}$ of 100% outperforms the same heuristic with $p_{reroute}$ 50% and 80% for the larger traffic samples. Improvements can be observed with statistically significant difference across all the traffic performance indicators tested for traffic sample size 500 and 200, with exception of total UAVs' queue counts in the network for the latter.

A similar trend is observed in the second part of the experiment, presented in Table 8.4 and Figure 8.5 where UAVs have different/mixed minimisation objectives as explained in subsection 8.3.1. Here again, $p_{reroute}$ of 100% showed time and energy reduction with a significant difference when compared to $p_{reroute}$ of 50% and 80%. Compared to the first part, Table 8.4 and Figure 8.5 showed a significant improvement for the total UAVs' travel time and energy consumption for GPD with $p_{reroute}$ 100% for larger traffic samples, regardless of the individual minimisation objective



(a) Impact on traffic time.

(b) Impact on traffic energy.



(c) Impact on path changes.

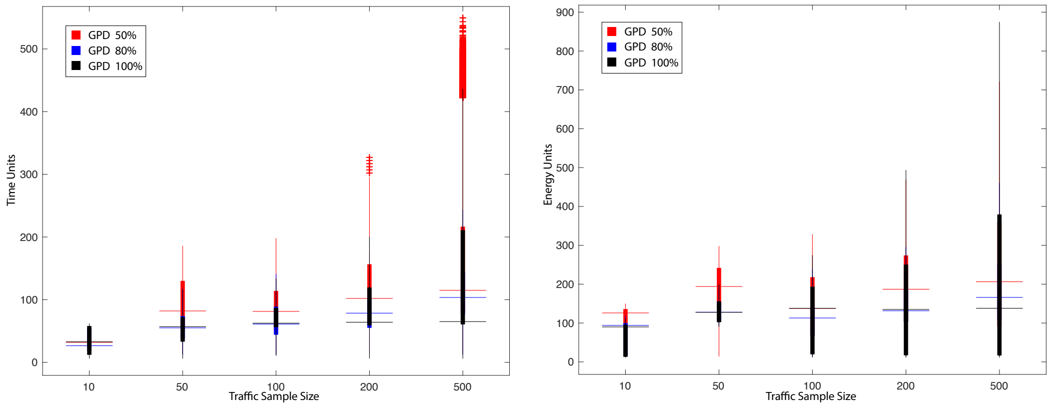
(d) Impact on layer changes.

FIGURE 8.4: Impact on traffic performance by varying $p_{rerouting}$ in GPD (50%, 80%, 100%).

Traffic	$p_{reroute}$	**Time**		**Energy**		**Path Changes**		**Layer Changes**		**Queue Counts**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
10	50%	**52.9**	**12.562**	**24.3**	**22.073**	1	0	6	0	**0**	**0**
	80%	55.22	13.532	24.913	24.122	0.733	0.442	4.4	2.657	0.267	0.442
	100%	59.57	14.195	26.063	27.518	**0.233**	**0.423**	**1.4**	2.541	0.767	0.423
50	50%	72.58	32.991	126.06	60.396	41	0	246	0	**0**	**0**
	80%	**71.609**	**31.663**	**113.490**	**52.779**	31.1	1.578	180.533	12.631	14.067	4.7127
	100%	95.709	54.985	142.730	85.650	**19.4**	**2.260**	**108.6**	**13.237**	46.767	6.683
100	50%	101.54	44.173	185.78	77.196	91	0	546	0	**41**	**0**
	80%	**97.807**	**41.408**	**168.034**	**71.125**	80.667	3.123	444.8	11.975	53.067	1.999
	100%	119.549	68.633	203.498	112.434	**55.533**	**2.391**	**311.4**	**14.881**	132.4	13.439
200	50%	184.77	98.680	321.89	152.576	323	0	1146	0	273	0
	80%	174.292	98.3507	293.762	153.836	241.2	4.942	1012.2	9.789	**255.767**	**2.362**
	100%	**155.051**	**79.231**	**274.623**	**138.601**	**142.333**	**3.261**	**790.667**	15.086	344.7	15.775
500	50%	403.158	218.089	692.006	359.752	2219	0	2946	0	2169	0
	80%	362.4707	200.818	626.507	340.444	1474.867	20.884	2746	8.884	2002.067	9.609
	100%	**317.376**	175.792	**560.534**	297.477	**660.667**	23.310	**2403.533**	23.408	**1932.6**	5.897

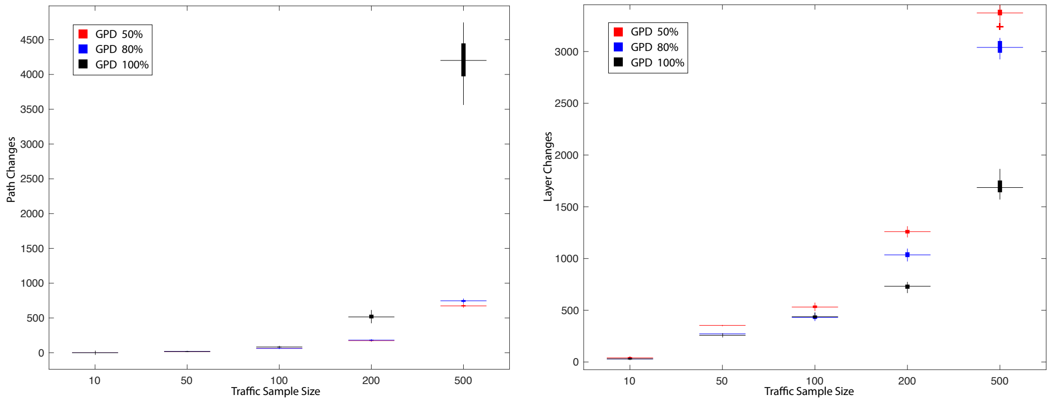
TABLE 8.4: Impact on mixed objective traffic performance from varying $p_{reroute}$ in GPD (50%, 80%, 100%).

of UAVs.



(a) Impact on traffic time.

(b) Impact on traffic energy.



(c) Impact on path changes.

(d) Impact on layer changes.

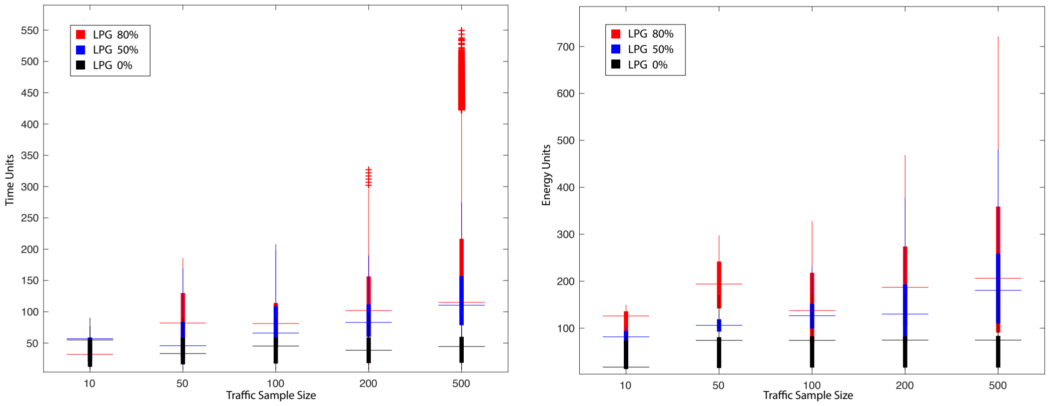
FIGURE 8.5: Impact on mixed objective traffic performance by varying $p_{reroute}$ in GPD (50%, 80%, 100%).

Experiment 3: Impact of T_{lim} on LPG Performance

Similar to the previous experiment and as explained in subsection 8.3.1, the impact on total UAVs' travel time and energy consumption in the network as well as the number of path changes, network layer change and queuing counts is explored as result of varying traffic threshold T_{lim} of LPG between 0%, 50% and 80% of c_l^{max}. Analysing the results obtained, it can be deduced from Table 8.5 and Figure 8.6 that, with the exception for the smallest traffic sample size of 10, LPG with T_{lim} of 0% generally showed improvement with statistically significant difference over T_{lim} of 80% and 50% across all the traffic performance indicators tested for the remaining traffic sample sizes. These results indicate that pheromone deposit caused a fast dispersion of UAVs across the network, which had a negative impact only for the smallest traffic sample. On the contrary, it led to an overall improvement in reducing total UAVs' travel time and energy consumption across for all other traffic samples.

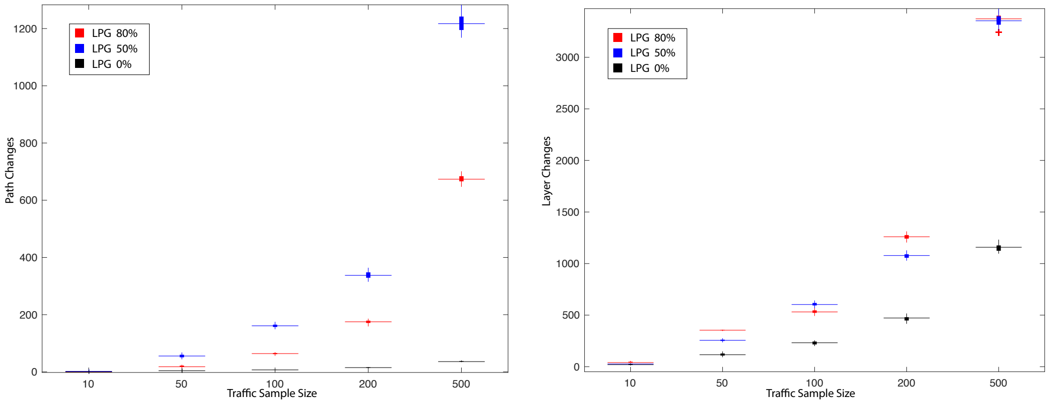
Experiment 4: Performance Comparison of GOS, GPD and LPG

Finally, Experiment 3 aims to study the performance of the three heuristics (GOS, GPD, LPG) in a more realistic scenario as explained in Section 8.3.1 to address the some of the limitations and assumptions made in the the first experiment [252]. Here each UAV has a different origin and destination pair as well as one of the two minimisation objectives (energy 7.11 or time 7.12).



(a) Impact on traffic time.

(b) Impact on traffic energy.



(c) Impact on path changes.

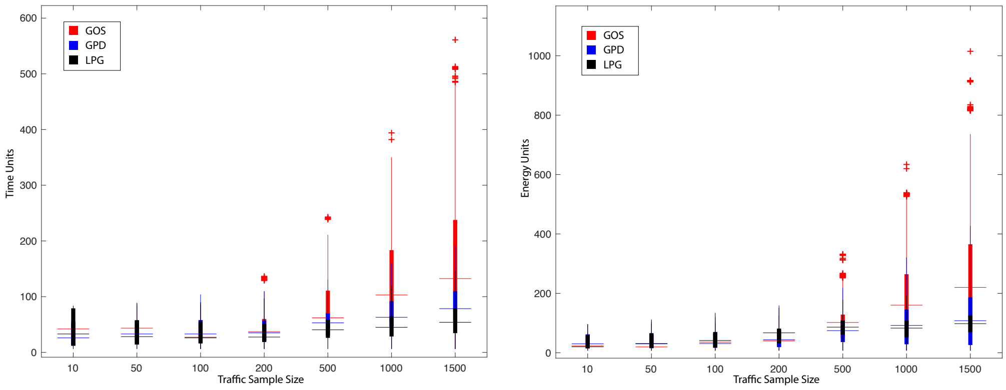
(d) Impact on layer changes.

FIGURE 8.6: Impact on traffic performance by varying T_lim in Local Pheromone Guided (LPG) (80%, 50%, 0%).

Traffic	T_{lim}	Time		Energy		Path Changes		Layer Changes		Queue Counts	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
10	80%	**35.897**	16.054	81.483	59.709	0.567	0.669	44	6.120	**0**	0
	50%	36.983	21.059	60.211	38.824	2.167	0.523	26.333	2.199	**0**	0
	0%	41.048	22.902	**42.883**	31.621	**0.033**	0.179	**19.2**	5.5131	0.033	0.179
50	80%	90.256	48.051	184.011	76.146	19.033	3.231	353.267	3.327	0.1	0.303
	50%	58.083	34.847	104.555	38.793	56.2	6.597	256.4	8.788	**0.033**	0.179
	0%	**38.535**	23.058	**60.263**	46.212	**3.767**	0.558	**118.267**	13.177	3.767	0.558
100	80%	87.8175	45.792	143.507	90.842	63.8	2.982	531.867	18.179	6	2.165
	50%	82.312	55.216	138.027	68.833	161.767	6.855	604.067	17.257	**0.667**	0.788
	0%	**39.929**	22.709	**59.784**	46.062	**7.2**	0.653	**230**	17.400	7.2	0.653
200	80%	113.014	61.736	188.479	113.829	174.5	6.329	1259.2	28.303	17.1	4.962
	50%	91.602	50.154	134.861	81.634	338.967	14.102	1079.4	31.008	**3.867**	1.857
	0%	**40.282**	22.734	**60.974**	46.324	**14.867**	1.118	**465.733**	26.967	14.867	1.117
500	80%	160.942	115.246	239.411	170.669	673.9	12.0816	3372.933	46.131	38.633	6.263
	50%	131.893	85.076	191.934	122.321	1218.333	37.382	3355.667	51.543	**35.6**	6.988
	0%	**40.798**	22.697	**60.925**	46.422	**37.067**	1.672	**1154**	33.765	37.067	1.672

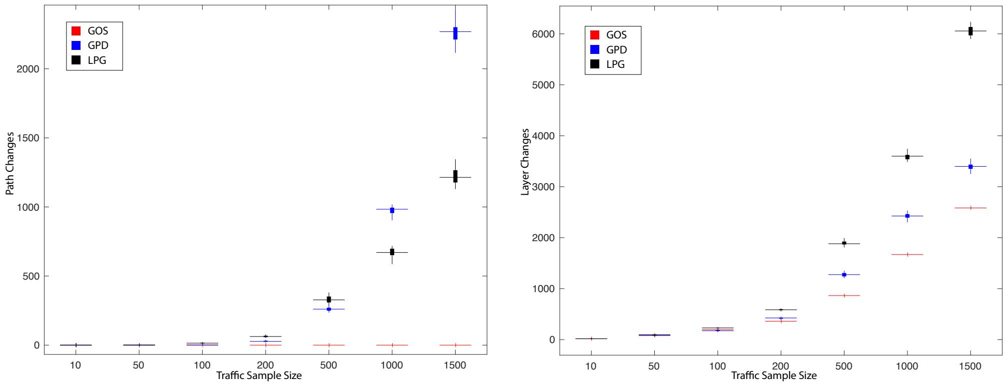
TABLE 8.5: Impact on traffic performance from varying traffic threshold in LPG (80%, 50%, 0%).

Figure 8.7 and Table 8.6 present the obtained results when comparing the impact the three heuristics (GOS, GPD, LPG) have on traffic performance in a more realistic scenario. It can be observed that, with the exception for traffic sample 10, LPG results show improvement in total UAVs' travel time for all traffic samples, where



(a) Comparison of total UAVs' travel time.

(b) Comparison of total UAVs' energy consumption.



(c) Comparison of total UAVs' path changes.

(d) Comparison of total UAVs' layer changes.

FIGURE 8.7: Performance comparison of GOS, GPD and LPG.

the percentage of UAVs with the minimisation objective 7.12 (i.e., time) is 50%, 40%, 45%, 19.5%, 48.8%, 49% and 48.13% for every traffic sample size respectively. On the other hand, it is worth to mention that due to the selected parameters and the nature of GPD, encouraging UAVs to be more inclined to reduce layer changes, led to the significant difference in reduction of energy consumption in comparison to LPG for traffic samples 50-200. However, for the larger traffic samples, which are more decisive in the devised scenario, LPG outperforms GPD with significant difference across 4 of the 5 main parameters of comparison, with the exception of total number of layer changes, which can be explained by the nature of the heuristic LPG which encourages UAVs to explore vertical airways between layers as they offer a higher c_l^{max}.

The main goal of Stage I was to verify the model, validate the initial results of the proposed optimisation approach and then test the UAV traffic performance using single objective optimisation. Over the 4 experiments detailed above, the best performing $p_{reroute}$ and T_{lim} were selected and finally all three proposed approaches where compared. As demonstrated in the final experiment, the LPG approach outperforms the other two approaches by reducing the total UAVs' traffic time and energy for the larger UAV traffic samples. To this end, the results obtained from Stage I would serve as basis for the multiobjective extension in Stage II, explored below.

Traffic	Heuristic	Time		Energy		Path Changes		Layer Changes		Queue Counts	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10	GOS	**36.6**	24.88	**33.2**	22.836	**0**	0	**16**	0	**0**	0
	GPD	37.005	27.297	37.468	25.579	**0**	0	17.933	7.006	**0**	0
	LPG	41.48	28.825	34.636	24.895	**0**	0	15.467	5.142	**0**	0
50	GOS	42.48	24.708	**36.12**	25.274	**0**	0	**80**	0	**0**	0
	GPD	40.075	27.126	38.069	26.758	0.2	0.603	84.6	12.759	**0**	0
	LPG	**38.567**	26.827	39.741	27.149	1.267	1.367	92	12.365	**0**	0
100	GOS	38.96	25.905	42.75	27.849	**0**	0	196	0	0	0
	GPD	40.551	26.048	**40.884**	28.378	2.133	1.707	**175.667**	13.811	0.167	0.453
	LPG	**36.05**	24.306	47.796	29.8793	13.6	4.957	228.733	8.982	**0**	0
200	GOS	46.755	31.381	52.42	35.264	**0**	0	**360**	0	17	0
	GPD	41.475	25.571	**51.0127**	32.667	27.8	4.527	420.6	15.512	4.767	2.458
	LPG	**34.823**	21.419	59.737	31.569	63.167	6.798	585.067	16.426	**0**	0
500	GOS	80.355	53.447	109.591	73.879	**0**	0	**864**	0	300	0
	GPD	54.502	32.649	**82.0328**	59.460	258.333	20.190	1275	38.084	101.433	10.941
	LPG	**45.676**	25.424	84.797	41.121	331	24.960	1895.533	49.837	**1.1**	1.247
1000	GOS	123.007	84.891	189.113	131.816	**0**	0	**1668**	0	1372	0
	GPD	76.069	50.318	111.649	101.295	982.433	40.802	2425.933	54.944	441.467	25.967
	LPG	**49.867**	27.228	**82.845**	42.786	670.5	33.059	3592.267	57.933	**10.433**	4.318
1500	GOS	162.340	114.463	264.691	193.237	**0**	0	**2584**	0	3097	0
	GPD	93.355	69.075	137.715	142.167	2267.9	81.103	3400.933	75.662	1059.033	66.985
	LPG	**59.887**	34.968	**100.8399**	53.280	1220.533	52.787	6051.533	96.466	**11.8**	4.490

TABLE 8.6: Comparison of traffic performance using GOS, GPD and LPG.

8.4 Stage II - Multiobjective Traffic Optimisation

The second stage (Stage II) of experimentation's main contribution is testing the Pareto-based multiobjective approaches in contrast to the single objective optimisation approaches in Stage I. To this end, this section extends the previous experiments in Section 8.3 by further exploring a more realistic scenario where a new airspace network instance as well as a realistic velocity–power model are used to test the traffic optimisation approach. The remainder of this section describes the experimental setup as well as the results obtained.

8.4.1 Experimental Setup

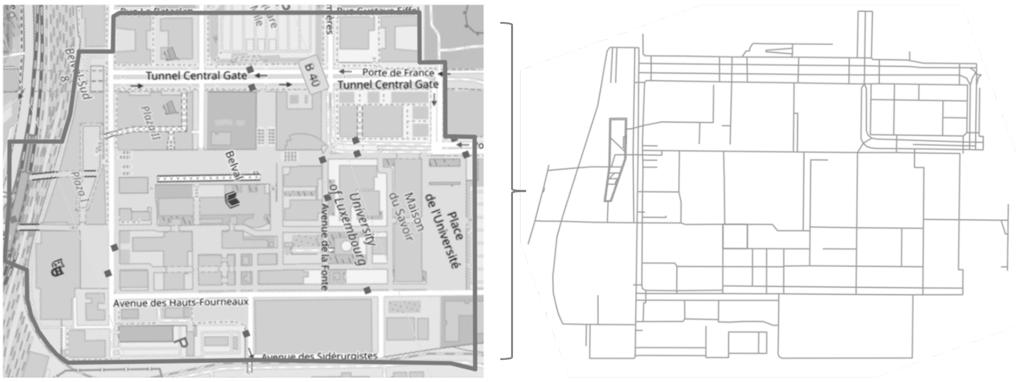


FIGURE 8.8: The network of streets and passages as extracted from OSM of the Belval Campus, University of Luxembourg.

For the second stage, experiments are conducted on a three layer network constructed using Python's NetworkX library and the multiNetX package comparable to that of Stage I, however, instead of the Erdős – Rényi model in the earlier stage, Stage II network is a three layer multilayer network of the Belval campus of the University of Luxembourg where the distance between each layer is 30 meters. The map

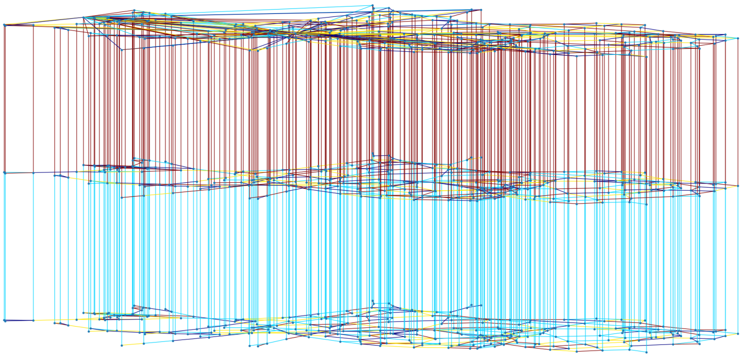


FIGURE 8.9: 3-layer network constructed based on OSM network of the Belval Campus, University of Luxembourg.

of the campus is constructed using Open Street Maps (OSM) [93] as shown in Figures 8.8 and 8.9. Additionally the second stage of experiments uses a more realistic velocity–power model adopted from the work in [113] using a multi-rotor UAV of six propellers and *P60-KV170* electric motors powered by a lithium polymer (LiPo) battery. The velocity–power model characteristic is shown in Figure 8.10. Further more, the parameters used for the experiments are described in Table 8.7.

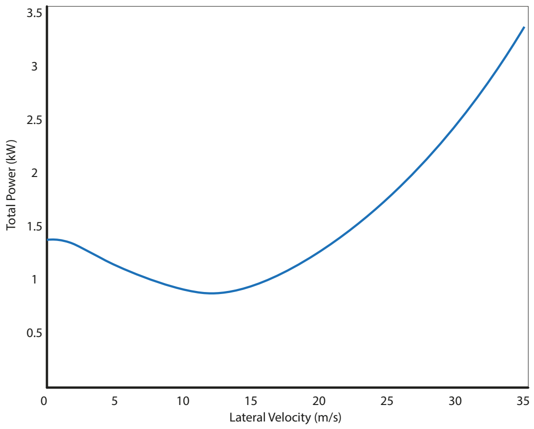


FIGURE 8.10: Illustration of the velocity-power curve.

Stage II is composed of the two main experiments described below:
For both experiments we compare the total UAVs' travel time in the network *in seconds*, the total UAVs' energy consumption *in joule*, as well as the number of path changes, network layer changes and total UAVs' queuing counts similarly to Stage I.

- **Experiment 1:** The first experiment aims to examine the performance of LPG approach of Stage I on the larger airspace network of Belval campus. The traffic threshold T_{lim} value of the single objective LPG that demonstrated best performance in Stage I is used. The results obtained from this experiment are compared to the Pareto front of the multiobjective optimisation approach and together would be used as comparative benchmark for results obtained from the Extended Local Pheromone Guided approach (eLPG).

- **Experiment 2:** The second experiment aims to investigate the traffic performance when using the eLPG multiobjective approach using the same value for T_{lim} as well as the same network parameters of the first experiment. The experiment explores the impact of using three variations of multiobjective A^* (MOA*) approaches. The results of this experiment are used to compare the performance against the obtained reference Pareto front as well as in terms of traffic performance indices of time and energy.

As shown in Table 8.7 a three-layer network with a total of 774 nodes and 1635 edges on all three layers based on the OSM of Belval is used for Stage II. The ranges of the airway maximum velocity limit were selected similar to those in Stage I to ensure that the lowest network layer allows less energy consumption by permitting UAVs to fly at their optimum or near optimum lateral velocity – *the velocity at which a UAV is most energy efficient benefiting from transitional lift* as explained in Chapter 5; while the higher layers allow incremental increase in flight velocity, hence reduce travel time at the cost of more energy consumption. Additionally, UAVs hovering in queuing state consume more energy than those in lateral flight. Furthermore, the selected capacity ranges also ensure that congestion can occur at different network layers for the tested UAV traffic values. Five traffic sample sizes were generated ranging from 10 to 1500 UAVs for the experiments. All UAVs are assigned a pair of origin and destination nodes, both located on the lowest layer. All pairs are similar for all experiments. Each UAV keeps record of its current position, destination as well as its total travel time and energy consumption. Simulations were run 30 times for probabilistic heuristics.

Parameter	**Value**
Number of UAVs	10, 50, 100, 200, 500
Number of nodes	258 per layer
Number of layers	3
Number of airway segments	1635
Interlayer velocity (ms^{-1})	10.5
Intralayer velocity intervals (ms^{-1})	[14,20],[20,26],[26,32]
Interlayer capacity weight interval	50
Intralayer capacity weight interval	[1,5]
LPG T_{lim} percentage of c_l^{max}	80%

TABLE 8.7: Stage II: experiment parameters.

8.4.2 Results and Analysis

This subsection presents the results of the second stage of experimentation and explores the findings [251]. The impact on the total UAVs' travel time in the network, total UAVs' energy consumption as well as the number of path changes, network layer change and queuing/hovering counts is explored similar to the first stage of simulations. All obtained results are presented in Figures 8.11–8.13 and summarised in Tables 8.8–8.12. Similar to the former stage, the box–plots in the figures present the impact in traffic performance by indicating the median, 25^{th} and 75^{th} percentile, while the tables additionally present the minimum, maximum, mean and standard deviation in the results after 30 runs of the stochastic approaches. Statistical confidence in our comparisons is assessed by performing the Wilcoxon rank test [308] for the first experiment and by performing the Kruskal-Wallis test [162] for the final experiment. The overall best result per comparison parameter is shown in bold. Additionally, the dark grey background emphasises the best results that showed statistically significant difference with a 95% confidence. In addition to the indices used in accessing the traffic performance, we use the set of metrics explained in Subsection 8.2.1 to evaluate the quality of results obtained by the different multiobjective approaches in the second experiment of this stage.

Experiment 1: Performance Evaluation of UAV Traffic with LPG

The first experiment aims to extend the first stage of simulations by exploring the performance of the different UAV traffic samples using the novel LPG algorithm presented in Stage I for dynamic path planning on the larger airspace network instance of the Belval campus, University of Luxembourg. Additionally the experiment uses a more realistic velocity–power model adopted from the work in [113] using a multi-rotor UAV of six propellers and *P60-KV170* electric motors powered by a lithium polymer (LiPo) battery. The traffic threshold T_{lim} value of the single objective LPG that demonstrated best performance in Stage I is used.
Figure 8.11 and Table 8.8 – 8.9 as well as additional results in Tables A.1 – A.6 in Appendix A present the obtained results.

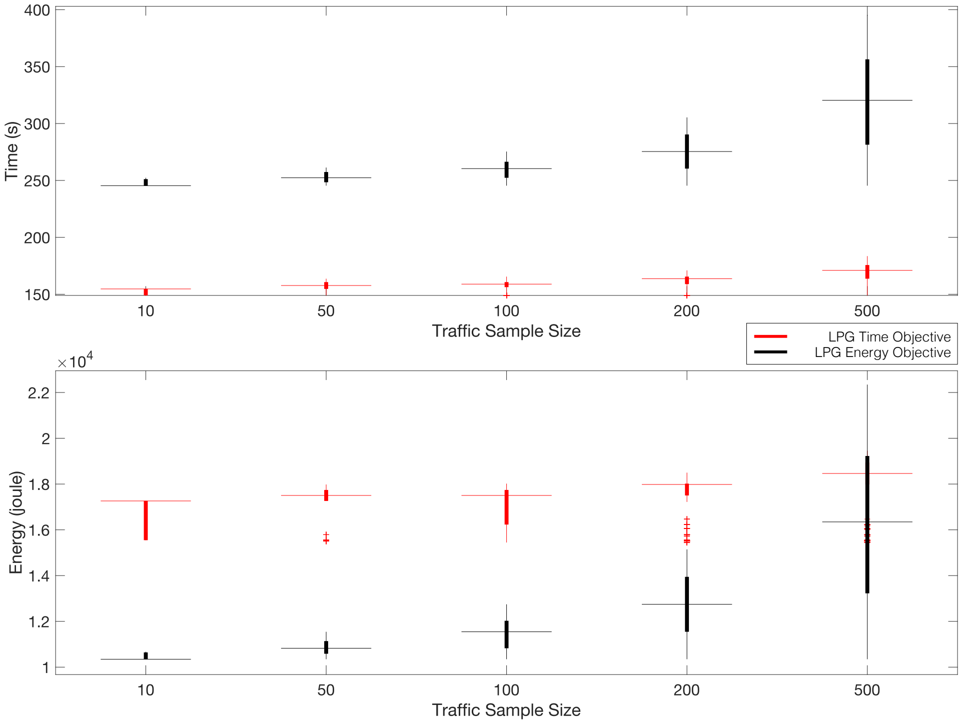


FIGURE 8.11: Total UAVs' time (**top**) and energy consumption (**bottom**) using single objective LPG.

Figure 8.11 illustrates the total UAVs' time (**top**) and energy consumption (**bottom**) using single objective LPG T and LPG E for time and energy respectively. The box–plots present the impact in traffic performance by indicating the median, 25^{th} and 75^{th} percentile where it can be observed that the trend follows that of Stage I. Looking at the larger UAV traffic sample size of 500 UAVs in Tables 8.8 – 8.9, one could notice that the minimum total UAVs' traffic time is 23.6 hours and minimum total UAVs' traffic energy is 8159 kJ. Moreover, Table A.1 shows that UAVs using the LPG

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	LPG T	1502,78	1524,01	**1512,97** 10,71	1502,78	1502,78	1524,01
	LPG E	2474,39	2476,62	2475,49 0,71	2475,42	2475,42	2475,58
50	LPG T	7859,05	7918,48	**7889,25** 25,81	7859,05	7888,81	7918,48
	LPG E	12631,25	12634,07	12632,62 0,92	12632,19	12632,71	12632,87
100	LPG T	15817,83	15870,65	**15840,28** 19,70	15819,57	15846,37	15846,97
	LPG E	26011,91	26014,99	26012,85 1,18	26011,91	26012,17	26013,28
200	LPG T	32275,40	32432,03	**32355,15** 62,53	32287,64	32379,79	32400,91
	LPG E	55021,88	55023,33	55022,31 0,54	55021,88	55022,14	55022,30
500	LPG T	84740,49	84932,95	**84851,23** 73,23	84799,80	84860,02	84922,91
	LPG E	160050,06	160054,85	160051,98 1,84	160050,06	160051,77	160053,14

TABLE 8.8: Total UAVs' time (s) using single objective LPG T (minimising time) and LPG E (minimising energy).

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	LPG T	165759,16	165759,16	165759,16 0,00	165759,16	165759,16	165759,16
	LPG E	104605,41	104631,72	**104615,94** 9,95	104605,41	104618,08	104619,06
50	LPG T	862720,99	869989,56	867314,73 3512,38	862720,99	869989,56	869989,56
	LPG E	543971,27	544683,24	**544289,61** 279,67	543984,92	544320,44	544488,20
100	LPG T	1713740,32	1721465,34	1717293,54 3016,44	1714321,10	1717097,76	1719843,18
	LPG E	1149897,06	1150400,34	**1150198,83** 165,14	1150218,93	1150218,93	1150258,89
200	LPG T	3518287,95	3535045,50	3524794,45 5902,15	3520163,41	3523697,47	3526777,93
	LPG E	2542378,74	2542586,45	**2542495,57** 95,80	2542378,74	2542560,14	2542573,79
500	LPG T	9161135,25	9169430,31	9164686,90 2685,11	9163807,46	9164308,92	9164752,55
	LPG E	8158536,27	8159219,98	**8158946,50** 256,18	8158858,15	8158898,10	8159219,98

TABLE 8.9: Total UAVs' energy (joule) using single objective LPG T (minimising time) and LPG E (minimising energy).

T approach averaged a lateral flight velocity of 23.94 m/s compared to 12.21 m/s for those using LPG E, indicating that the latter opted for occupying the lower layers of the airspace while the former preferred the higher layers for shorter travel times. To this end, the results obtained in the first experiment of this stage of experimentation further support the initial hypothesis of this work and offer additional validation to the proposed distributed model of UAV traffic management and that in a more realistic instance UAVs relying on local knowledge and digital stigmergy communicated through digital pheromone deposition on the network airways manage to adapt their flight behaviour in terms of number of path changes, layer changes and holding patterns to achieve their objective. Tables A.1 – A.6 present additional results that explore the average UAV lateral velocities in the various traffic samples, the average UAV battery percentage consumption, the average path length taken by each UAV in every traffic sample as well as changes in path, altitude layer and queuing/hovering.

Experiment 2: Performance Comparison of UAV Traffic with eLPG using three different MOA^* Approaches

The second experiment aims to investigate the traffic performance when using the eLPG multiobjective approaches. The experiment explores the impact of using three variation of implementation of multiobjective A^* approaches as explained in Chapter 7. The decision making criteria weights are equal for *eLPG Static TOPSIS* and vary with percentage battery consumption for *eLPG Dynamic TOPSIS* and *eLPG Dynamic BOA** as explained in the previous chapter of this work. The results of this experiment are used for performance evaluation in terms of traffic performance indices of time and energy as well as for evaluation of the obtained and reference Pareto fronts. Figure 8.12 and Table 8.10 – 8.11 present the obtained results comparing the total UAVs' traffic time and energy while Figure 8.13 and Table 8.12 present the obtained fronts and respective metrics. Before applying these metrics, all fronts were normalised.

Figure 8.12 illustrates the total UAVs' time (**top**) and energy consumption (**bottom**) using three multiobjective eLPG approaches. When comparing the results for the larger UAV traffic sample size of 500 UAVs in Tables 8.10 – 8.11, one could notice that the minimum total UAVs' traffic time is 31.6 hours and minimum total UAVs' traffic energy is 9203 kJ. Additionally, Figure 8.12 shows that while the eLPG with static TOPSIS criteria outperforms both eLPG with dynamic TOPSIS and dynamic BOA* in total UAVs traffic time, UAVs using eLPG with dynamic BOA* achieve more energy efficient results for larger traffic samples. Moreover, Table A.7 – A.9 show that UAVs using the eLPG with static TOPSIS averaged a lateral flight velocity of 18.2 m/s and consumed an average of 12.4% of their batteries on a 3.99 km flight path compared to 13.9 m/s for those using eLPG with dynamic TOPSIS and 13.6 m/s for UAVs following the eLPG with dynamic BOA*, the latter consumed 11.6% and 10.2% of their batteries on average for a comparable flight path of 3.989 km.

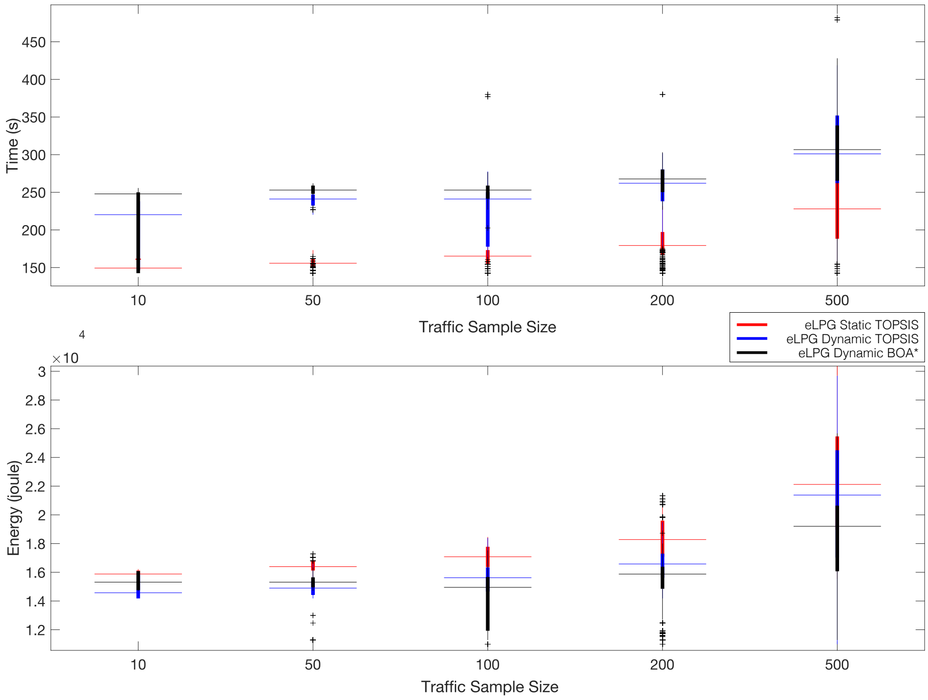


FIGURE 8.12: Total UAVs' time –*top* and energy –*bottom* using eLPG.

The results presented in Tables 8.10 and 8.11 further support the findings illustrated in Figure 8.12 where eLPG approach relying on a fixed MCDM matrix - Static TOPSIS - outperforms the other MOA* in minimising time over all the tested traffic samples with statistical significance for sample sizes 10, 50 and 100 UAVs. In contrast using a dynamically changing MCDM matrix that takes into consideration the consumption of battery resulted in an improved over all traffic energy consumption. Table 8.11 shows that eLPG with Dynamic Biobjective A* (Dynamic BOA*) resulted in reduced total traffic energy followed by eLPG with Dynamically varying TOPSIS criteria weights. One interesting finding observed when comparing the results with those obtained with single objective LPG over the same network instance, is that for

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	1483,21	1504,78	**1497,48** 9,28	1489,84	1504,78	1504,78
	eLPG Dynamic TOPSIS	1817,90	2015,31	1943,33 73,62	1906,21	1979,73	1997,52
	eLPG Dynamic BOA*	2019,33	2077,12	2052,02 24,83	2025,07	2069,30	2069,30
50	eLPG Static TOPSIS	7785,79	7888,81	**7856,26** 42,24	7829,07	7888,81	7888,81
	eLPG Dynamic TOPSIS	10872,66	11302,10	11160,13 177,83	11030,50	11293,50	11301,89
	eLPG Dynamic BOA*	11725,51	12235,61	12023,20 166,18	12024,63	12053,53	12076,71
100	eLPG Static TOPSIS	16307,18	16581,00	**16501,91** 102,78	16488,39	16564,41	16568,59
	eLPG Dynamic TOPSIS	22117,63	22466,43	22352,31 125,57	22357,08	22366,25	22454,14
	eLPG Dynamic BOA*	24220,56	24377,49	24303,58 59,38	24251,54	24315,98	24352,33
200	eLPG Static TOPSIS	36085,78	36271,94	**36137,40** 69,45	36089,71	36105,04	36134,52
	eLPG Dynamic TOPSIS	49528,08	49867,28	49738,70 112,73	49752,05	49768,28	49777,82
	eLPG Dynamic BOA*	51958,50	52175,97	52112,49 80,11	52124,69	52128,25	52175,06
500	eLPG Static TOPSIS	113596,37	117286,12	**114407,55** 1442,89	113604,18	113683,49	113867,57
	eLPG Dynamic TOPSIS	150324,75	151822,26	151305,48 532,42	151205,85	151489,30	151685,22
	eLPG Dynamic BOA*	150871,78	151311,41	151035,76 169,53	150888,27	150957,80	151149,53

TABLE 8.10: Total UAVs' time (s) with eLPG using three different MOA^* approaches.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	159347,86	159745,96	159469,17 161,85	159347,86	159347,86	159556,32
	eLPG Dynamic TOPSIS	148441,86	152396,95	**149879,10** 1450,01	148834,31	149226,77	150495,63
	eLPG Dynamic BOA*	153326,58	154679,93	153859,04 512,88	153326,58	153885,52	154076,62
50	eLPG Static TOPSIS	822273,90	825620,86	823110,06 1298,87	822273,90	822273,90	823107,75
	eLPG Dynamic TOPSIS	749023,20	761444,07	**755051,95** 4362,84	752388,60	754221,05	758182,84
	eLPG Dynamic BOA*	752741,08	759423,12	756304,07 2231,31	755213,65	757023,49	757119,04
100	eLPG Static TOPSIS	1702545,38	1705620,99	1704424,02 1116,23	1703832,35	1704843,13	1705278,23
	eLPG Dynamic TOPSIS	1559037,58	1566308,20	1561548,43 2636,50	1559425,90	1560706,44	1562264,04
	eLPG Dynamic BOA*	1431616,38	1437318,18	**1434648,45** 2144,32	1433286,02	1434230,24	1436791,45
200	eLPG Static TOPSIS	3656565,06	3675830,02	3661521,57 7196,92	3658184,93	3658201,23	3658826,62
	eLPG Dynamic TOPSIS	3311813,00	3318498,03	3315312,68 2684,88	3312448,88	3316477,01	3317326,50
	eLPG Dynamic BOA*	3029591,07	3035169,52	**3032384,09** 2163,25	3030189,07	3032950,90	3034019,86
500	eLPG Static TOPSIS	11055987,60	11365640,77	11119421,46 123138,35	11058182,27	11058368,75	11058927,93
	eLPG Dynamic TOPSIS	10486914,25	10519251,60	10502135,97 12433,20	10492856,40	10497625,64	10514031,97
	eLPG Dynamic BOA*	9202910,95	9216648,32	**9208512,72** 4924,82	9204191,28	9208106,46	9210706,61

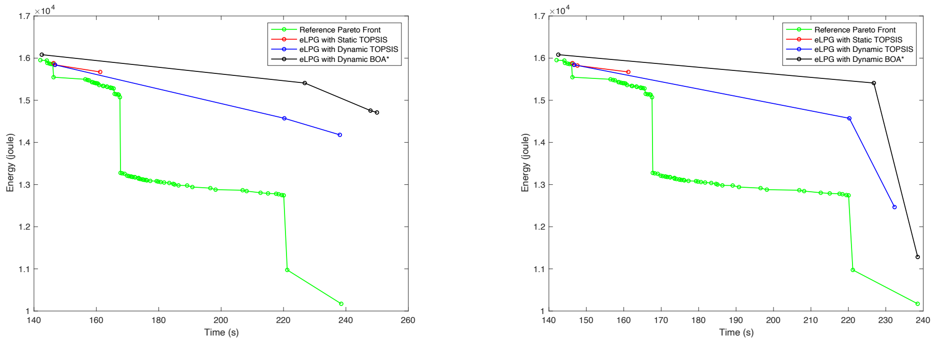
TABLE 8.11: Total UAVs' energy (joule) with eLPG using three different MOA^* approaches.

Metric	Traffic	eLPG Static TOPSIS	eLPG Dynamic TOPSIS	eLPG Dynamic BOA*
HV	10	**7,478E-01** 1,034E-01	7,402E-01 3,008E-02	6,959E-01 1,807E-02
	50	**7,941E-01**. 4,965E-16	7,524E-01 3,811E-02	7,550E-01 2,186E-02
	100	7,647E-01 6,556E-02	6,986E-01 5,463E-03	**7,745E-01** 2,677E-02
	200	7,647E-01 6,556E-02	7,006E-01 4,327E-03	**7,745E-01** 2,677E-02
	500	7,647E-01 6,556E-02	7,067E-01 9,262E-03	**7,843E-01** 2,186E-02
Δ	10	–	**1,161E+00** 9,012E-02	1,401E+00 1,251E-01
	50	1 0	1,096E+00 1,014E-01	**7,639E-01** 1,320E-01
	100	1,070E+00 1,566E-01	1,372E+00 1,048E-02	**8,819E-01** 1,617E-01
	200	1,070E+00 1,566E-01	1,368E+00 1,382E-02	**8,819E-01** 1,617E-01
	500	1,070E+00 1,566E-01	1,347E+00 3,802E-02	**9,410E-01** 1,320E-01
IGD	10	8,360E-01 3,124E-01	**6,346E-01** 3,450E-02	7,033E-01 3,097E-02
	50	6,963E-01 1,986E-15	**6,605E-01** 3,905E-02	8,022E-01 5,916E-02
	100	**7,082E-01** 2,650E-02	8,797E-01 4,053E-03	7,492E-01 7,246E-02
	200	**7,082E-01** 2,650E-02	8,809E-01 8,961E-05	7,492E-01 7,246E-02
	500	**7,082E-01** 2,650E-02	8,784E-01 8,408E-03	7,228E-01 5,916E-02

TABLE 8.12: Comparison of the three approaches used by means of HV, Δ and IGD metrics (median and inter-quartile range values).

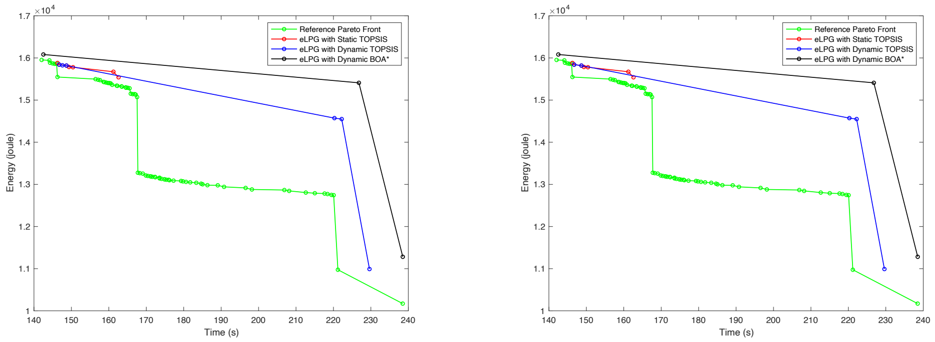
traffic sample sizes 10 and 50 UAVs the eLPG with Static TOPSIS outperformed the single objective LPG in total UAV traffic time. One possible explanation is due to the fact that the multiobjective variant reduced congestion in the network.

The obtained Pareto fronts as well as the evaluation metric results presented in Figure 8.13 and Table 8.12 in addition to TablesA.13 - A.14 indicate that eLPG Dynamic



(a) Fronts for traffic sample 10.

(b) Fronts for traffic sample 50.



(c) Fronts for traffic sample 100.

(d) Fronts for traffic sample 500.

FIGURE 8.13: Representation of obtained Pareto fronts from the three approaches for 3 traffic samples.

BOA* outperforms the other algorithms on instance sizes of 50 - 500 UAVs according to HV, SP and Δ with statistical significance with the exception for the smaller instance where eLPG Dynamic TOPSIS outperformed Dynamic BOA*. However, in the case of GD, IGD and consequently Δ_P eLPG Static TOPSIS outperforms the other algorithms with statistical significance with the exception for instance sizes 10 and 50 where Dynamic TOPSIS outperforms.

To this end, the main contribution of this stage of experimentation was testing the Pareto-based multiobjective approaches proposed in Chapter 7. In contrast to Stage I in Section 8.3, this section of the work used a more realistic scenario including an empirically derived velocity–power model as well as an airspace network instance extracted from OSM.

8.5 Discussions

In this chapter, we explained our simulation and experimentation methodology. We firstly described the performance indices and evaluation metrics followed by our simulation procedure and instance model. The experiments were conducted on two stages, the first stage focused on the validation and verification of the model and parameters. At the initial stage, a single optimisation objective is considered and the performance of the first three proposed algorithms - GOS, GPD and LPG - is compared. The latter stage of experimentation extends and builds on the first stage where it introduces more realistic simulation instances and airspace model and tests the performance of traffic when implementing a more complex multiobjective optimisation model.

To this end, the experimentation and analysis confirmed the initial claim that with larger traffic demands, the way-point path planning systems of centralised UTM would result in significantly lower traffic operational performance and efficiency. The work also led to the conclusions with the aid of the devised framework of traffic performance metrics, that the proposed optimisation algorithms LPG and eLPG led to statistically significant improvements of 43% in total traffic time and 24% in total traffic energy for traffic sample size of 500 UAVs and 63.5% in total traffic time and 61.9% in total traffic energy for traffic samples of 1500 UAVs. This in turn emphasises the correlation between the effectiveness of the distributed traffic optimisation and the traffic demands.

While the results showed a promising outcome, there are many ways where the optimisation model can be extended for further investigation in order to be able to practically implement a fully distributed UTM. Some of these include: i) exploring the traffic behaviour with larger number of network layers and additional cost functions; ii) investigating potential automation of efficient UAV behaviours generation using a unique combination of optimisation and machine learning, such as hyper-heuristics [52]; investigate the impact of different decision making criteria on the behaviour of traffic. Whilst the simulation included assumptions to simplify the challenging multifaceted problem, future work should should consider more realistic communication scenarios and investigate different communication protocols on traffic behaviour given the challenging nature of flying ad-hoc networks.

End of Chapter 8

Part III

Conclusion Remarks

Chapter 9

Conclusions and Perspectives

9.1 Summary

This thesis addressed one of the pressing issues when it comes to the future of unmanned aviation and that is how to safely incorporate them into our low-altitude airspace and manage their operation efficiently and safely.

In order to propose a novel solution, **Part I** of the manuscript presented an overview of the background and notions of the foundational technologies and concepts used throughout the work, namely IoT and UAVs.
As IoT continues to transform the aerospace sector, UAVs stand out as one clear example that continues to witness great evolution over the years. Most notably, the shift UAVs have undergone from solely aerial vehicles with applications dominated in the military field to mobile IoT-connected smart devices and platforms with unprecedented use cases in almost every commercial domain.
This technological evolution that led the rapid growth of the global commercial UAV market, translates to a rapid expansion in the number of autonomous UAVs expected to operate within a limited shared resource, the low-altitude airspace over the coming years. Making it safe to envision a near future where cities airspace is dominated by autonomous flying vehicles on missions ranging from regular aerial data collection to on-demand delivery, medical emergency intervention to more demanding applications requiring sophisticated beyond line-of-sight multi-UAV swarm operations. **Part I** of the work concludes by highlighting the new set of obstructing challenges that need to be addressed in order to realise the full potential of UAVs and emphasising the role of standardisation and research in taking on such endeavour.

Part II of the manuscript dives into thorough analysis of the state-of-the art in UAV traffic management through Chapters 4 to 8 and presents the main contributions of the work.
Firstly, the work focused on providing an elaborate introduction and overview of UAV Traffic Management (UTM) systems, conceptual constructs and regulatory frameworks that exist in literature and industry. Secondly, the work explored the role of

UTM in airspace management and the required key functionalities.
Given the hypothesis that a fully autonomous UTM with distributed decision making allows for better scalability and resilience, the main goal the remainder of the manuscript from Chapter 5 onward was to investigate the feasibility of the hypothesis by examining the possibility of developing a fully distributed UTM that is capable of intelligently handling highly dynamic and challenging traffic conditions. To this end every chapter of the manuscript focuses on addressing one of the research questions highlighted in Chapter 1.
Chapter 5 explored the strategic airspace management aspect of UTM by investigating and assessing how the structure of the airspace can be defined and how UAVs traffic can be modelled, presenting our first contribution towards the devised distributed UTM, a novel low-altitude airspace structure and model that extends existing literature and adopts key well-established standards from manned aviation.
Chapter 6 built on Chapter 5 by investigating the tactical airspace management aspect of UTM by exploring the UAV information exchange and connectivity infrastructure, presenting the second key contribution of the manuscript by devising an information exchange framework that allows autonomous UAV operation by enabling a hybrid and decentralised information exchange through UAV-to-UAV and UAV-to-Infrastructure communication.
Chapter 7 and 8 addressed the core functions of UTM by exploring and evaluating traffic behaviour based on proposed path planning optimisation algorithms that address the research question of whether local UAV behaviour can lead to global traffic improvement.

9.2 Conclusions and perspectives

This section presents our conclusions as well as future perspective. Chapter 1 presented our hypothesis that an UTM with distributed decision making would allow for better scalability and resilience. To this end, given that the work showed the performance insufficiency of centralised systems as result of their inadequacy in efficiently optimising large UAV traffic, and further illustrated through experimentation that a dUTM system outperforms the centralised approaches, it is therefore safe to conclude the validity of the hypothesis of the work given an adequate communication system and airspace structure.
Since the scope of this statement is broad, the following subsections delve into each of the main aspects as a response to the corresponding research questions stated in Section 1.2.2 of the work.

A Distributed UAV Traffic Management System

In contribution to this field, the manuscript presented a comprehensive literature study on UAVs with specific focus on state-of-the-art technological advancements and inherent challenges as they become part of the ubiquitous network of connected things. Complementing and extending to the latter, the work presented a thorough study on UTM systems including a comparative analysis of existing and currently underdevelopment UTM constructs' architectures and functionalities.

To this end, the thesis concluded that existing UTM systems should expect to face limitations due to their ATM-comparable architectures with the foreseen large UAV traffic demands in the near future. The manuscript highlighted the paramount role of technical standardisation in guiding UTM developments. In addition to the more than eight key functionalities identified in the manuscript for a successful UTM, the thesis deduced that in order to develop a fully distributed UTM capable of handling fully autonomous UAV traffic the following aspects are of significant importance, namely, airspace structure, information exchange as well as traffic optimisation and technical standardisation as detailed in the below subsections.

Additionally, the experimental simulation results of the proposed system showed improvement in addressing large autonomous UAV traffic when compared to existing centralised solutions. Nevertheless, throughout our work, we made some assumptions to abstract the multifaceted problem in compliance with the delimitation of the research topic and hence, we indicated eventual challenges that could arise in a practical implementation of a fully distributed UTM. To this end, the following subsections will discuss aspects of the system where there could be potential improvement in future research work and standardisation work.

9.2.1 Airspace Model

To address the first research question of how UAV traffic can be modelled in the low-altitude airspace, the work presented a novel structure for the uncontrolled low-altitude Class G airspace combining benefits from various proposed structures in literature. The work additionally presented a formal model of the airspace as a dynamic multi-weighted multilayer network of nodes and airways to serve as a foundation to addressing the complex problem of distributed UTM.

To this end, the thesis concluded that airspace structure plays a significant role in traffic management at both a strategic and a tactical level. At the strategic level, the presented work emphasised a direct correlation between the degree of structure of the airspace and density and volume of traffic flow management as well as its operational efficiency.

One potential area where the model can be further extended is by incorporating transitional layers as well as the assignment of headings to the different layers. Another addition could be a formal representation of dynamic geo-limitation in the multilayer network. At the time of writing this manuscript, SDOs are drafting international standards and guidelines on how to represent obstacles within the airspace and how to define time-bound geo-limits.

9.2.2 Information Exchange Model

While Section 9.2.1 addressed the first part of the first research question by devising the airspace model, this section addressed the information exchange model.

In this context, the work deduced through Chapters 4 to 6 that for UAVs to operate within a network of digital/virtual airways in contrast to a physical network infrastructure such as tunnels, bridges and highways in vehicular networks, further convoluted by the higher degree of mobility of UAVs and the sub-centimetre position precision requirements, mean that there is a greater reliance on more efficient information exchange for tactical airspace management when compared to road vehicles. The thesis additionally emphasised the importance of efficient and secure data and information exchange. While UAV communications is a well-established broad research domain and out of scope of the core of this work, the thesis proposed a novel distributed UTM generic information exchange model based on a hybrid Flight Information Management Systems approach incorporating new developments in aerial communications to accommodate for future autonomous flight planning. The thesis additionally concluded that lack of UAV-specific communication international technical standards contributes significantly to the obstruction of global harmonisation.

To comply with the delimitation of the research, the work did not consider communication metrics in the evaluation of simulations. Additionally for simplicity, the experimentation stage assumed perfect communication links. Two obvious extensions could be i) to explore means of combining 5G and other communication technologies for navigation; ii) to include a more realistic communication model to the simulation that takes into account interference caused by city structures.

9.2.3 Traffic Optimisation and Deconfliction Model

To address the second and third research questions presented in Section 1.2.2 on i) how optimisation models can be defined to encompass problem-specific constraints such as 3D mobility and objectives such as time and energy consumption; ii) how distributed UAV behaviours can be designed to benefit the global traffic system. The thesis provided a new optimisation model taking into consideration the UAVs higher degree of mobility as well as operational limitations. The work additionally proposed and evaluated two stages experimentation varying in the level of complexity and number of optimisation objectives. The outcomes of the work were a Local Pheromone Guided Algorithm (LPG) for single objective UAV traffic optimisation and an Extended Local Pheromone Guided Algorithm (eLPG) as a novel distributed path planning algorithm for autonomous UAVs allowing each UAV to plan its path relying on local knowledge gained via digital stigmergy while simultaneously addressing conflict resolution at three distinct levels.

The experimentation and analysis confirmed the initial claim that with larger traffic demands, the way-point path planning systems of centralised UTM would result in significantly lower traffic operational performance and efficiency. The work also led to the conclusions with the aid of the devised framework of traffic performance metrics, that the proposed optimisation algorithms LPG and eLPG led to statistically significant improvements in overall traffic performance with a 95% confidence across all evaluation criteria used at different stages of experimentation.

While the results showed a promising outcome, there are many ways where the optimisation model can be extended for further investigation in order to be able to practically implement a fully distributed UTM. Some of these include: i) exploring the traffic behaviour with larger number of network layers and additional cost functions such as connectivity or collision risk; ii) investigating potential automation of efficient UAV behaviours generation using a unique combination of optimisation and machine learning, such as hyper-heuristics [52]; investigate the impact of different decision making criteria on the behaviour of traffic.

9.2.4 Technical Standardisation

With regard of the last research question on the significance and role of standardisation UTM development, the thesis provided a comprehensive literature study on emerging computing paradigms as enablers to the digital transformation being witnessed in UAVs shift to smart connected devices. The manuscript highlighted the key concepts and notions in IoT as well as developments and challenges in security, data protection and privacy from scientific research and technical standardisation stand points.

Following the thorough analysis of the predominant gaps between IoT scientific research and standardisation, the work concluded that security, data protection and privacy are perceived as the main pillars of trust. The work hence contributed to literature by extending an interpretation of the concept of digital trust and derivation of a definition of trustworthiness in emerging IoT-connected digital technologies. Additionally, the thesis included and adopted national, regional and international IoT, UAV and aerospace technical standards throughout all proposed models and architecture in the manuscript with the aim of aligning scientific research and technical standardisation.

The analysis indicated the need of harmonisation of research work and consensus between SDOs to avoid standards duplication and ensure harmonisation that would foster UAV and UTM developments. One other potential direction emphasised throughout this thesis is the need of establishing a standardised IoT-dedicated risk assessment framework. The benefit of the framework is to complement existing impact assessment guidelines in accurately identifying, estimating/quantifying and prioritising risk strategies for IoT-connected devices and platforms such as UAVs. Such a framework would be a step in enforcing compliance with GDPR, on one hand, and bridging the gap between market needs, research and standardisation, on the other.

9.3 Final remarks

Emerging computing paradigms and specifically the Internet of Things are disrupting industries and as IoT continues to transform the aerospace industry, new value-added services, applications and enhanced customer experience continue to emerge. However, with all technological advancements come obstructing challenges.

This dissertation followed a unique interdisciplinary, holistic and proactive approach to addressing some of these inevitable future challenges fuelled by our rapid transition into a fully–connected digital and information era that obstruct the realisation of unmanned commercial aviation to its full potential.
More specifically, this work integrated and brought together tools, techniques and concepts from aerospace engineering, computer science and technical standardisation to advance the fundamental understanding of digital trustworthiness and present a solution framework for the safe management of autonomous unmanned aerial vehicles.

The multifaceted, multi-modal approach followed throughout this dissertation has led to the identification of some critical gaps between the standardisation efforts and scientific research but has also made contributions to both domains. The work emphasised that in response to market readiness and maturity levels, technical standards help shape new regulatory models, and together act as technology safeguards to guide the economy. This in turn encourages market competition by lowering barriers to entry for newcomers. Creating the perfect petri dish for innovation. An environment and culture that drives research to create new methods that catalyse new value-added use-cases in the market, in turn challenging and systematically evaluating standards.

To this end, the thesis additionally deduced that the lag in development of required technical standards has short term benefits in reducing time to market of non-standardised UTM sub-systems such as obstacle data structures, communication models and remote identification. However, the work concludes that over the long run, adopting and endorsing evolving standards goes beyond merely showing commitment to promoting an open approach and would eventually allow early adopters the opportunity to shape the technology landscape by promoting patented intellectual property and preferred technical approaches, in turn, creating additional revenue. Furthermore, early adoption of international standards would prevent future global harmonisation challenges such as a forklift update as the case was with telecommunication companies.

End of Chapter 9

Appendix A

Additional Results

This Appendix A presents the additional results tables obtained from the experimentation section of the work in Chapter 8.

A.1 Stage II Experiment I

Tables A.1 – A.6 present additional traffic performance indices exploring the average UAV lateral velocities, the average path length taken by each UAV in every traffic sample as well as changes in path, altitude layer and hovering.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	LPG T	25,96	27,04	**26,39** 0,53	25,96	25,96	27,04
	LPG E	15,44	15,71	15,62 0,07	15,63	15,63	15,63
50	LPG T	24,53	27,04	**25,43** 0,64	24,99	25,47	25,96
	LPG E	14,73	15,68	15,27 0,26	15,07	15,25	15,44
100	LPG T	24,53	26,56	**25,49** 0,59	24,99	25,47	25,96
	LPG E	13,92	15,71	14,80 0,53	14,39	14,73	15,25
200	LPG T	23,67	26,56	**24,94** 0,72	24,53	24,90	25,47
	LPG E	12,56	15,71	14,02 0,92	13,20	13,92	14,73
500	LPG T	21,89	26,56	**23,94** 1,09	23,26	23,67	24,53
	LPG E	9,70	15,71	12,21 1,70	10,76	11,97	13,63

TABLE A.1: Average UAV velocity (m/s) using single objective LPG T (minimising time) and LPG E (minimising energy).

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	LPG T	3955,98	4015,98	3991,98 29,69	3955,98	4015,98	4015,98
	LPG E	3834,69	3946,93	**3866,13** 48,53	3834,69	3834,69	3938,05
50	LPG T	3954,69	4015,98	4007,77 20,74	4015,98	4015,98	4015,98
	LPG E	3834,69	3938,77	**3855,84** 41,86	3834,69	3834,69	3834,69
100	LPG T	3954,69	4247,25	4035,10 73,40	4015,98	4015,98	4015,98
	LPG E	3834,69	3946,93	**3846,32** 32,78	3834,69	3834,69	3834,69
200	LPG T	3954,69	4247,25	4032,07 62,16	4015,98	4015,98	4015,98
	LPG E	3834,69	3946,93	**3840,09** 23,06	3834,69	3834,69	3834,69
500	LPG T	3954,69	4247,25	4055,24 82,49	4015,98	4015,98	4015,98
	LPG E	3834,69	3946,93	**3836,90** 15,01	3834,69	3834,69	3834,69

TABLE A.2: Average UAV length of path taken (m) using single objective LPG T (minimising time) and LPG E (minimising energy).

Traffic	**Approach**	**Min**	**Max**	**Mean** SD	η_{25}	**Median**	η_{75}
10	LPG T	8,822	9,590	9,283 0,380	8,822	9,590	9,590
	LPG E	5,748	5,928	**5,812** 0,080	5,748	5,748	5,913
50	LPG T	8,613	9,990	9,646 0,381	9,590	9,723	9,856
	LPG E	5,748	6,414	**6,048** 0,190	5,881	6,014	6,188
100	LPG T	8,581	10,010	9,541 0,485	9,017	9,723	9,856
	LPG E	5,748	7,081	**6,390** 0,395	6,014	6,414	6,681
200	LPG T	8,581	10,277	9,791 0,441	9,723	9,990	10,010
	LPG E	5,748	8,414	**7,062** 0,778	6,414	7,081	7,748
500	LPG T	8,581	10,810	10,183 0,470	9,990	10,256	10,523
	LPG E	5,748	12,414	**9,065** 1,929	7,348	9,081	10,681

TABLE A.3: Average UAV 180kj battery consumed (%) using single objective LPG T (minimising time) and LPG E (minimising energy).

Traffic	**Approach**	**Min**	**Max**	**Mean** SD	η_{25}	**Median**	η_{75}
10	LPG T	6,00	6,00	6,00 0,00	6,00	6,00	6,00
	LPG E	3,00	3,00	**3,00** 0,00	3,00	3,00	3,00
50	LPG T	44,00	46,00	45,20 0,98	44,00	46,00	46,00
	LPG E	8,00	12,00	**10,20** 1,60	9,00	10,00	12,00
100	LPG T	109,00	113,00	111,40 1,63	110,00	112,00	113,00
	LPG E	10,00	13,00	**11,20** 0,98	11,00	11,00	11,00
200	LPG T	227,00	230,00	228,40 1,02	228,00	228,00	229,00
	LPG E	10,00	11,00	**10,40** 0,49	10,00	10,00	11,00
500	LPG T	684,00	688,00	686,40 1,36	686,00	687,00	687,00
	LPG E	9,00	13,00	**10,60** 1,50	9,00	11,00	11,00

TABLE A.4: Total UAVs′ path changes using single objective LPG T (minimising time) and LPG E (minimising energy).

Traffic	**Approach**	**Min**	**Max**	**Mean** SD	η_{25}	**Median**	η_{75}
10	LPG T	52,00	52,00	52,00 0,00	52,00	52,00	52,00
	LPG E	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00
50	LPG T	284,00	288,00	286,40 1,96	284,00	288,00	288,00
	LPG E	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00
100	LPG T	544,00	550,00	547,20 2,40	546,00	546,00	550,00
	LPG E	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00
200	LPG T	1142,00	1152,00	1146,40 3,44	1144,00	1146,00	1148,00
	LPG E	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00
500	LPG T	2934,00	2948,00	2941,20 5,15	2938,00	2940,00	2946,00
	LPG E	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00

TABLE A.5: Total UAVs′ layer changes using single objective LPG T (minimising time) and LPG E (minimising energy).

Traffic	**Approach**	**Min**	**Max**	**Mean** SD	η_{25}	**Median**	η_{75}
10	LPG T	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00
	LPG E	1,00	1,00	1,00 0,00	1,00	1,00	1,00
50	LPG T	56,00	72,00	**65,60** 7,85	56,00	72,00	72,00
	LPG E	96,00	104,00	99,60 3,21	96,00	100,00	102,00
100	LPG T	104,00	119,00	**111,00** 4,98	108,00	112,00	112,00
	LPG E	464,00	470,00	467,60 1,96	468,00	468,00	468,00
200	LPG T	409,00	460,00	**437,20** 21,87	413,00	447,00	457,00
	LPG E	1958,00	1960,00	1959,20 0,98	1958,00	1960,00	1960,00
500	LPG T	2143,00	2214,00	**2183,00** 27,36	2162,00	2186,00	2210,00
	LPG E	12424,00	12432,00	12428,80 2,99	12428,00	12428,00	12432,00

TABLE A.6: Total UAVs' hovering/queuing count using single objective LPG T (minimising time) and LPG E (minimising energy).

A.2 Stage II Experiment II

Tables A.7 – A.12 present additional traffic performance indices for the second experiment in Stage II exploring the average UAV lateral velocities, the average path length taken by each UAV in every traffic sample as well as changes in path, altitude layer and hovering. Moreover, the section presents additional evaluation metrics for the multiobjective approaches in Tables A.13 and A.14.

Traffic	**Approach**	**Min**	**Max**	**Mean** SD	η_{25}	**Median**	η_{75}
10	eLPG Static TOPSIS	24,5368	27,0419	**26,4590** 0,8238	26,4985	26,4985	27,0419
	eLPG Dynamic TOPSIS	16,6124	26,9592	21,4953 5,0875	16,6124	17,9543	26,9592
	eLPG Dynamic BOA*	15,8270	27,7579	20,8343 5,7356	15,9595	16,1680	27,7579
50	eLPG Static TOPSIS	22,8370	27,0419	**25,2438** 1,1773	24,5270	25,4013	26,4191
	eLPG Dynamic TOPSIS	15,6277	27,0352	18,4600 4,2039	16,0073	16,4057	16,7628
	eLPG Dynamic BOA*	15,1020	27,7579	17,0544 3,8442	15,2769	15,6393	15,9910
100	eLPG Static TOPSIS	20,6874	27,0419	**24,3361** 1,5684	23,2307	24,4591	25,4746
	eLPG Dynamic TOPSIS	14,6915	26,9592	18,5553 4,1694	15,8152	16,4057	23,1758
	eLPG Dynamic BOA*	14,6003	27,7579	16,9387 3,5183	15,2769	15,8270	16,0822
200	eLPG Static TOPSIS	17,0877	27,0419	**22,2849** 2,4257	20,3611	22,0646	24,4472
	eLPG Dynamic TOPSIS	12,9245	26,9592	16,5791 3,8998	13,8927	15,0910	16,6124
	eLPG Dynamic BOA*	12,9803	27,7579	15,5665 2,8921	14,1310	15,1020	15,9516
500	eLPG Static TOPSIS	12,0401	27,0419	**18,2304** 3,8813	14,8559	17,6048	21,0099
	eLPG Dynamic TOPSIS	9,3614	26,9592	13,9102 3,6882	11,2331	13,3224	15,0910
	eLPG Dynamic BOA*	10,4374	27,7579	13,6568 2,8734	11,5721	13,1560	15,1020

TABLE A.7: Average UAV velocity (m/s) with eLPG using three different *MOA** approaches.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	3955,98	4068,98	3958,27 15,98	3955,98	3955,98	3955,98
	eLPG Dynamic TOPSIS	3954,69	3956,12	**3955,35** 0,72	3954,69	3954,69	3956,12
	eLPG Dynamic BOA*	3955,98	4134,10	3982,82 59,52	3955,98	3955,98	3955,98
50	eLPG Static TOPSIS	3954,69	4068,98	3957,76 13,97	3955,98	3955,98	3955,98
	eLPG Dynamic TOPSIS	3894,69	4068,98	**3955,68** 10,90	3954,69	3954,69	3954,69
	eLPG Dynamic BOA*	3834,69	4134,10	3962,63 54,41	3955,98	3955,98	3955,98
100	eLPG Static TOPSIS	3954,69	4366,62	3998,69 87,21	3955,98	3955,98	3957,41
	eLPG Dynamic TOPSIS	3834,69	4215,25	**3980,04** 72,76	3954,69	3954,69	3956,12
	eLPG Dynamic BOA*	3834,69	5677,31	3994,00 173,25	3955,98	3955,98	4014,10
200	eLPG Static TOPSIS	3954,69	4366,62	3980,98 67,03	3955,98	3955,98	3956,12
	eLPG Dynamic TOPSIS	3834,69	4215,25	**3957,46** 62,98	3954,69	3954,69	3955,98
	eLPG Dynamic BOA*	3834,69	5677,31	3964,82 144,79	3895,98	3955,98	3955,98
500	eLPG Static TOPSIS	3954,69	4398,52	3994,93 87,66	3955,98	3955,98	3956,12
	eLPG Dynamic TOPSIS	3834,69	4366,62	**3989,03** 92,80	3954,69	3954,69	3956,12
	eLPG Dynamic BOA*	3834,69	5677,31	3989,20 161,75	3948,84	3955,98	4014,10

TABLE A.8: Average UAV length of path taken (m) with eLPG using three different MOA^* approaches.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	8,7067	9,0095	8,8594 0,0900	8,8225	8,8225	8,9558
	eLPG Dynamic TOPSIS	7,8776	8,9339	**8,3266** 0,4520	7,8776	8,0956	8,8005
	eLPG Dynamic BOA*	8,1725	8,9343	8,5477 0,3423	8,1971	8,5077	8,9343
50	eLPG Static TOPSIS	8,7067	9,6005	9,1457 0,2242	8,9558	9,1067	9,3558
	eLPG Dynamic TOPSIS	6,9252	9,6005	**8,3895** 0,4408	8,0109	8,2776	8,5443
	eLPG Dynamic BOA*	6,2677	9,4677	8,4034 0,5818	8,3058	8,5077	8,6941
100	eLPG Static TOPSIS	8,6336	10,2547	9,4690 0,4073	9,0892	9,4892	9,8769
	eLPG Dynamic TOPSIS	6,1062	10,2196	8,6753 0,7426	8,1443	8,6776	9,0776
	eLPG Dynamic BOA*	6,2677	9,7343	**7,9703** 1,0552	6,6265	8,3058	8,7058
200	eLPG Static TOPSIS	8,6336	11,8580	10,1709 0,8225	9,4892	10,1558	10,8869
	eLPG Dynamic TOPSIS	6,1062	11,8547	9,2092 0,8875	8,6776	9,2109	9,6109
	eLPG Dynamic BOA*	6,2677	10,4010	**8,4233** 1,0369	8,2515	8,8201	9,1058
500	eLPG Static TOPSIS	8,6336	16,8681	12,3549 2,1122	10,5339	12,2892	14,1462
	eLPG Dynamic TOPSIS	6,1062	16,4948	11,6690 2,3902	9,4585	11,8776	13,6109
	eLPG Dynamic BOA*	6,2677	14,2677	**10,2317** 1,9309	8,9274	10,6680	11,4677

TABLE A.9: Average UAV 180kj battery consumed (%) with eLPG using three different MOA^* approaches.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	1,00	2,00	**1,60** 0,49	1,00	2,00	2,00
	eLPG Dynamic TOPSIS	4,00	6,00	5,40 0,81	5,00	6,00	6,00
	eLPG Dynamic BOA*	6,00	6,00	6,00 0,00	6,00	6,00	6,00
50	eLPG Static TOPSIS	11,00	15,00	**13,40** 1,96	11,00	15,00	15,00
	eLPG Dynamic TOPSIS	39,00	43,00	41,60 1,75	40,00	43,00	43,00
	eLPG Dynamic BOA*	41,00	46,00	43,80 1,60	44,00	44,00	44,00
100	eLPG Static TOPSIS	55,00	70,00	**63,60** 4,85	64,00	64,00	65,00
	eLPG Dynamic TOPSIS	105,00	109,00	107,40 1,50	107,00	107,00	109,00
	eLPG Dynamic BOA*	96,00	99,00	97,40 1,02	97,00	97,00	98,00
200	eLPG Static TOPSIS	86,00	115,00	**103,40** 9,57	103,00	106,00	107,00
	eLPG Dynamic TOPSIS	218,00	219,00	218,60 0,49	218,00	219,00	219,00
	eLPG Dynamic BOA*	195,00	201,00	197,20 2,23	195,00	197,00	198,00
500	eLPG Static TOPSIS	253,00	297,00	**267,60** 16,50	254,00	260,00	274,00
	eLPG Dynamic TOPSIS	644,00	657,00	649,80 4,79	645,00	651,00	652,00
	eLPG Dynamic BOA*	540,00	546,00	541,60 2,25	540,00	541,00	541,00

TABLE A.10: Total UAVs' path changes with eLPG using three different MOA^* approaches.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	40,00	40,00	40,00 0,00	40,00	40,00	40,00
	eLPG Dynamic TOPSIS	40,00	40,00	40,00 0,00	40,00	40,00	40,00
	eLPG Dynamic BOA*	40,00	40,00	40,00 0,00	40,00	40,00	40,00
50	eLPG Static TOPSIS	200,00	200,00	200,00 0,00	200,00	200,00	200,00
	eLPG Dynamic TOPSIS	198,00	200,00	199,60 0,80	200,00	200,00	200,00
	eLPG Dynamic BOA*	188,00	190,00	**188,80** 0,98	188,00	188,00	190,00
100	eLPG Static TOPSIS	400,00	400,00	400,00 0,00	400,00	400,00	400,00
	eLPG Dynamic TOPSIS	390,00	390,00	390,00 0,00	390,00	390,00	390,00
	eLPG Dynamic BOA*	258,00	262,00	**259,60** 1,50	258,00	260,00	260,00
200	eLPG Static TOPSIS	800,00	800,00	800,00 0,00	800,00	800,00	800,00
	eLPG Dynamic TOPSIS	706,00	710,00	708,00 1,79	706,00	708,00	710,00
	eLPG Dynamic BOA*	504,00	512,00	**506,40** 2,94	504,00	506,00	506,00
500	eLPG Static TOPSIS	2000,00	2004,00	2002,00 1,79	2000,00	2002,00	2004,00
	eLPG Dynamic TOPSIS	1842,00	1852,00	1846,80 4,12	1842,00	1848,00	1850,00
	eLPG Dynamic BOA*	1140,00	1156,00	**1146,80** 5,60	1144,00	1144,00	1150,00

TABLE A.11: Total UAVs' layer changes with eLPG using three different MOA^* approaches.

Traffic	Approach	Min	Max	Mean SD	η_{25}	Median	η_{75}
10	eLPG Static TOPSIS	4,00	4,00	4,00 0,00	4,00	4,00	4,00
	eLPG Dynamic TOPSIS	0,00	1,00	0,20 0,40	0,00	0,00	0,00
	eLPG Dynamic BOA*	0,00	0,00	**0,00** 0,00	0,00	0,00	0,00
50	eLPG Static TOPSIS	129,00	136,00	130,40 2,81	129,00	129,00	129,00
	eLPG Dynamic TOPSIS	103,00	116,00	111,00 4,44	110,00	113,00	113,00
	eLPG Dynamic BOA*	78,00	80,00	**79,60** 0,80	80,00	80,00	80,00
100	eLPG Static TOPSIS	449,00	460,00	453,80 5,08	450,00	450,00	460,00
	eLPG Dynamic TOPSIS	388,00	393,00	389,60 2,06	388,00	388,00	391,00
	eLPG Dynamic BOA*	176,00	190,00	**184,60** 4,97	184,00	184,00	189,00
200	eLPG Static TOPSIS	1982,00	2086,00	2006,00 40,08	1987,00	1987,00	1988,00
	eLPG Dynamic TOPSIS	1982,00	2005,00	1996,80 8,28	1994,00	2000,00	2003,00
	eLPG Dynamic BOA*	1221,00	1237,00	**1227,00** 6,42	1221,00	1224,00	1232,00
500	eLPG Static TOPSIS	12809,00	14112,00	13080,40 515,99	12819,00	12824,00	12838,00
	eLPG Dynamic TOPSIS	13722,00	13792,00	13752,40 24,90	13732,00	13750,00	13766,00
	eLPG Dynamic BOA*	10025,00	10070,00	**10042,20** 15,49	10031,00	10041,00	10044,00

TABLE A.12: Total UAVs' hovering/queuing count with eLPG using three different MOA^* approaches.

Metric	Traffic	eLPG Static TOPSIS	eLPG Dynamic TOPSIS	eLPG Dynamic BOA*
SP	10	–	**9,979E-01** 5,578E-01	1,650E+00 3,703E-01
	50	0 0	6,990E-01 6,460E-01	**2,591E-02** 1,448E-02
	100	3,200E-01 7,156E-01	8,465E-01 1,410E-02	**1,295E-02** 1,774E-02
	200	3,200E-01 7,156E-01	8,510E-01 9,560E-03	**1,295E-02** 1,774E-02
	500	3,200E-01 7,156E-01	8,776E-01 4,753E-02	**6,476E-03** 1,448E-02
GD	10	1,910E-01 6,817E-02	1,492E-01 6,338E-03	**1,463E-01** 4,775E-02
	50	**1,605E-01** 3,401E-15	1,639E-01 2,445E-02	3,242E-01 9,148E-02
	100	**1,738E-01** 2,973E-02	3,097E-01 2,193E-02	2,423E-01 1,120E-01
	200	**1,738E-01** 2,973E-02	3,176E-01 1,769E-02	2,423E-01 1,120E-01
	500	**1,738E-01** 2,973E-02	3,217E-01 8,932E-03	2,014E-01 9,148E-02
Δ_P	10	8,360E-01 3,124E-01	**6,346E-01** 3,450E-02	7,033E-01 3,097E-02
	50	6,963E-01 1,986E-15	**6,605E-01** 3,905E-02	8,022E-01 5,916E-02
	100	**7,082E-01** 2,650E-02	8,797E-01 4,053E-03	7,492E-01 7,246E-02
	200	**7,082E-01** 2,650E-02	8,809E-01 8,961E-05	7,492E-01 7,246E-02
	500	**7,082E-01** 2,650E-02	8,784E-01 8,408E-03	7,228E-01 5,916E-02

TABLE A.13: Comparison of the three approaches used by means of SP, GD and Δ_P metrics (median and inter-quartile range values).

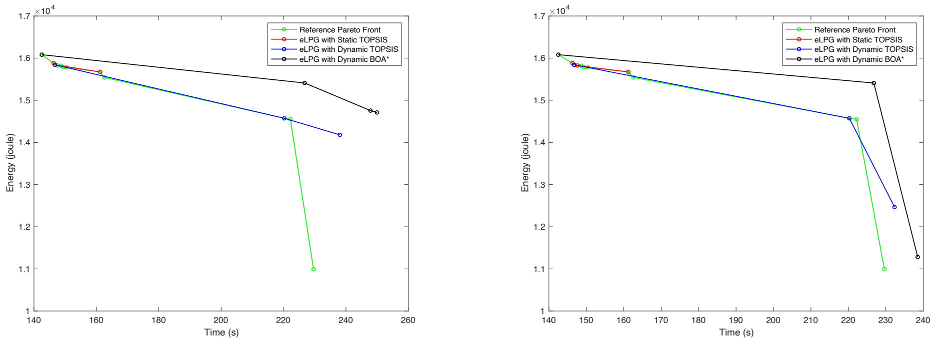
Metric	Traffic	eLPG Static TOPSIS	eLPG Dynamic TOPSIS	eLPG Dynamic BOA*
HV	10	**7,478E-01** 1,034E-01	7,402E-01 3,008E-02	6,959E-01 1,807E-02
	50	**7,941E-01.** 4,965E-16	7,524E-01 3,811E-02	7,550E-01 2,186E-02
	100	7,647E-01 6,556E-02	6,986E-01 5,463E-03	**7,745E-01** 2,677E-02
	200	7,647E-01 6,556E-02	7,006E-01 4,327E-03	**7,745E-01** 2,677E-02
	500	7,647E-01 6,556E-02	7,067E-01 9,262E-03	**7,843E-01** 2,186E-02
SP	10	–	**9,979E-01** 5,578E-01	1,650E+00 3,703E-01
	50	0 0	6,990E-01 6,460E-01	**2,591E-02** 1,448E-02
	100	3,200E-01 7,156E-01	8,465E-01 1,410E-02	**1,295E-02** 1,774E-02
	200	3,200E-01 7,156E-01	8,510E-01 9,560E-03	**1,295E-02** 1,774E-02
	500	3,200E-01 7,156E-01	8,776E-01 4,753E-02	**6,476E-03** 1,448E-02
Δ	10	–	**1,161E+00** 9,012E-02	1,401E+00 1,251E-01
	50	1 0	1,096E+00 1,014E-01	**7,639E-01** 1,320E-01
	100	1,070E+00 1,566E-01	1,372E+00 1,048E-02	**8,819E-01** 1,617E-01
	200	1,070E+00 1,566E-01	1,368E+00 1,382E-02	**8,819E-01** 1,617E-01
	500	1,070E+00 1,566E-01	1,347E+00 3,802E-02	**9,410E-01** 1,320E-01
GD	10	1,910E-01 6,817E-02	1,492E-01 6,338E-03	**1,463E-01** 4,775E-02
	50	**1,605E-01** 3,401E-15	1,639E-01 2,445E-02	3,242E-01 9,148E-02
	100	**1,738E-01** 2,973E-02	3,097E-01 2,193E-02	2,423E-01 1,120E-01
	200	**1,738E-01** 2,973E-02	3,176E-01 1,769E-02	2,423E-01 1,120E-01
	500	**1,738E-01** 2,973E-02	3,217E-01 8,932E-03	2,014E-01 9,148E-02
IGD	10	8,360E-01 3,124E-01	**6,346E-01** 3,450E-02	7,033E-01 3,097E-02
	50	6,963E-01 1,986E-15	**6,605E-01** 3,905E-02	8,022E-01 5,916E-02
	100	**7,082E-01** 2,650E-02	8,797E-01 4,053E-03	7,492E-01 7,246E-02
	200	**7,082E-01** 2,650E-02	8,809E-01 8,961E-05	7,492E-01 7,246E-02
	500	**7,082E-01** 2,650E-02	8,784E-01 8,408E-03	7,228E-01 5,916E-02
Δ_P	10	8,360E-01 3,124E-01	**6,346E-01** 3,450E-02	7,033E-01 3,097E-02
	50	6,963E-01 1,986E-15	**6,605E-01** 3,905E-02	8,022E-01 5,916E-02
	100	**7,082E-01** 2,650E-02	8,797E-01 4,053E-03	7,492E-01 7,246E-02
	200	**7,082E-01** 2,650E-02	8,809E-01 8,961E-05	7,492E-01 7,246E-02
	500	**7,082E-01** 2,650E-02	8,784E-01 8,408E-03	7,228E-01 5,916E-02

TABLE A.14: Comparison of the three approaches used by means of HV, SP, Δ, GD, IGD and Δ_P metrics (median and inter-quartile range values).

Reference front combined:

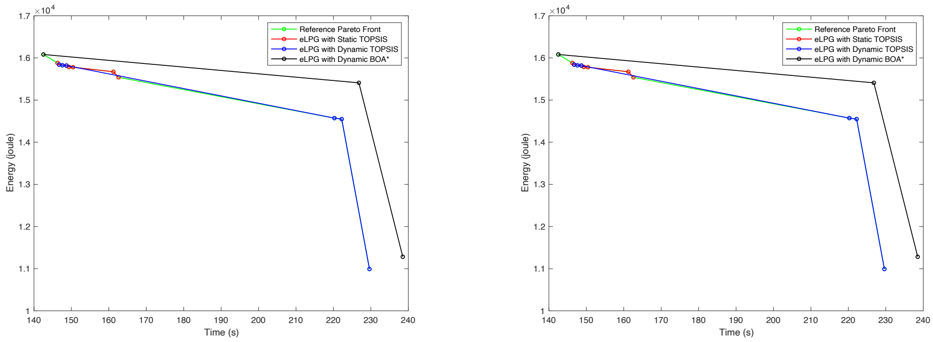
Metric	Traffic	eLPG Static TOPSIS	eLPG Dynamic TOPSIS	eLPG Dynamic BOA*
IGD	10	**7,02E-01** 1,95E-01	8,98E-01 1,59E-01	1,02E+00 7,83E-02
	50	**6,14E-01**4,32E-15	8,21E-01 1,89E-01	7,67E-01 8,53E-02
	100	**5,79E-01** 7,85E-02	6,66E-01 1,07E-01	6,90E-01 1,04E-01
	200	**5,79E-01** 7,85E-02	7,04E-01 8,62E-02	6,90E-01 1,04E-01
	500	**5,79E-01** 7,85E-02	7,13E-01 6,85E-02	6,52E-01 8,53E-02
GD	10	**3,67E-01** 1,43E-01	4,39E-01 4,39E-03	4,68E-01 4,03E-02
	50	**4,31E-01** 4,39E-15	4,36E-01 4,91E-03	4,43E-01 6,89E-03
	100	3,94E-01 8,11E-02	**3,46E-01** 5,35E-02	4,37E-01 8,44E-03
	200	3,94E-01 8,11E-02	**3,66E-01** 4,35E-02	4,37E-01 8,44E-03
	500	3,94E-01 8,11E-02	**3,83E-01** 6,44E-03	4,34E-01 6,89E-03
HV	10	4,04E-01 2,26E-01	**4,98E-01** 4,21E-03	4,65E-01 7,94E-03
	50	**5,05E-01** 1,99E-15	4,96E-01 1,23E-02	4,79E-01 1,45E-02
	100	4,65E-01 9,10E-02	4,24E-01 8,78E-03	**4,92E-01** 1,77E-02
	200	4,65E-01 9,10E-02	4,27E-01 6,89E-03	**4,92E-01** 1,77E-02
	500	4,65E-01 9,10E-02	4,32E-01 4,15E-03	**4,99E-01** 1,45E-02
Spacing	10	-	**9,98E-01** 5,58E-01	1,65E+00 3,70E-01
	50	**0** 0	6,99E-01 6,46E-01	2,59E-02 1,45E-02
	100	3,20E-01 7,16E-01	8,46E-01 1,41E-02	**1,30E-02** 1,77E-02
	200	3,20E-01 7,16E-01	8,51E-01 9,56E-03	1,30E-02 1,77E-02
	500	3,20E-01 7,16E-01	8,78E-01 4,75E-02	6,48E-03 1,45E-02
Spread	10	-	**1,18E+00** 1,02E-01	1,43E+00 1,61E-01
	50	1,00E+00 0,00E+00	1,11E+00 1,15E-01	**6,94E-01** 1,71E-01
	100	1,10E+00 2,19E-01	1,57E+00 5,47E-02	**8,47E-01** 2,10E-01
	200	1,10E+00 2,19E-01	1,55E+00 5,49E-02	**8,47E-01** 2,10E-01
	500	1,10E+00 2,19E-01	1,50E+00 4,87E-02	**9,23E-01** 1,71E-01
DeltaP	10	**7,02E-01** 1,95E-01	8,98E-01 1,59E-01	1,02E+00 7,83E-02
	50	**6,14E-01** 4,32E-15	8,21E-01 1,89E-01	7,67E-01 8,53E-02
	100	**5,79E-01** 7,85E-02	6,76E-01 1,16E-01	6,90E-01 1,04E-01
	200	**5,79E-01** 7,85E-02	7,18E-01 9,38E-02	6,90E-01 1,04E-01
	500	**5,79E-01** 7,85E-02	7,26E-01 7,59E-02	6,52E-01 8,53E-02

TABLE A.15: Comparison of the three approaches used by means of HV, SP, Δ, GD, IGD and Δ_P metrics (median and inter-quartile range values).



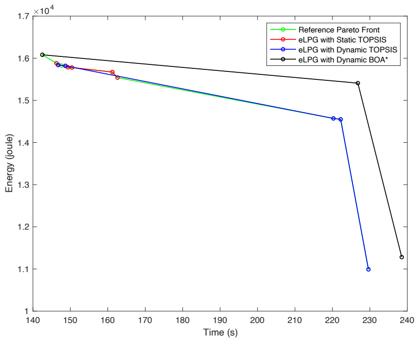
(a) Fronts for traffic sample 10.

(b) Fronts for traffic sample 50.



(c) Fronts for traffic sample 100.

(d) Fronts for traffic sample 200.



(e) Fronts for traffic sample 500.

FIGURE A.1: Comparison of obtained Pareto fronts from the three approaches for all traffic samples.

The above tables present additional results obtained from the experimentation and referred to in Chapter 8.

End of Appendix A

Appendix B

Scientific Dissemination

This Appendix B highlights the relevant publications and articles, summarised in Table B.1 and detailed in the below sections, submitted and presented during the PhD work as means of disseminating scientific content.

Dissemination	
B.1 Scientific Journals	[253][166]
B.2 Conferences & Workshops	[251][252][256]
B.3 Technical Reports	[257][255].
B.4 Scientific Articles	[254]

TABLE B.1: Summary of PhD Publications.

B.1 Scientific Journals

[166] **N. S. Labib** et al. ”The Rise of Drones in Internet of Things: A survey on the evolution, prospects and challenges of Unmanned Aerial Vehicles”. In: *IEEE ACCESS* vol. 9 (2021), pp. 115466-115487.

[253] **N. S. Labib** et al. ”Internet of Unmanned Aerial Vehicles: A Multilayer Low-Altitude Airspace Model for Distributed UAV Traffic Management”. In: *Sensors* 19.21 (2019), p. 4779.

B.2 International Conferences & Workshops

[251] **N. S. Labib** et al. ”A Distributed Pareto-based Path Planning Algorithm for Autonomous Unmanned Aerial Vehicles”. In: *WoMAPF 20 in conjunction with 29th International Joint Conferences on Artificial Intelligence (IJCAI)*. Jan 2021.

[252] **N. S. Labib** et al. ”A Multilayer Low-Altitude Airspace Model for UAV Traffic Management”. In Proceedings of: *9th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications DIVANet19. ACM*, Nov. 2019.

[256] **N. S. Labib** et al. ”Trustworthiness in IoT – A Standards Gap Analysis on Security, Data Protection and Privacy”. In Proceedings of: *5th IEEE Conference on Standards for Communications and Networking (CSCN)*. Oct. 2019.

B.3 Technical Reports

[255] **N. S. Labib** et al. Technical Report on Data Protection and Privacy in Smart ICT: Internet of Things – Gap Analysis between Scientific Research and Technical Standardisation: Gap Analysis Internet of Things. Tech. rep. *ILNAS*, 2019.

[257] **N. S. Labib** et al. White Paper: Data Protection and Privacy in Smart ICT – Scientific Research and Technical Standardisation. Tech. rep. *ILNAS*, 2018.

B.4 Scientific Articles

[254] **N. S. Labib** et al. ”On Standardised Localisation and Tracking Systems for UAVs in Smart Cities”. In: 17th *Annual STS Conference Graz, Critical Issues in Science, Technology and Society Studies*. 2018.

End of Appendix B

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